Ref. Ares(2018)2848949 - 31/05/2018

Integrated Arctic Observation System

Research and Innovation Action under EC Horizon2020
Grant Agreement no. 727890

Project coordinator:
Nansen Environmental and Remote Sensing Center, Norway

Deliverable 2.7

Report on present observing capacities and gaps: Land and cryosphere

Start date of project:	01 December 2016	Duration:	60 months
Due date of deliverable:	31 May 2018	Actual submission date:	31 May 2018
Lead beneficiary for preparing the deliverable:		USFD	
Person-months used to produce deliverable:		42.5 pm	

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Version	DATE	CHANGE RECORDS	LEAD AUTHOR
1.0	30/04/2017	Template	Roberta Pirazzini
1.1	14/12/2017	1st Draft	Roberta Pirazzini
1.2	1/04/2018	2nd Draft (Sect. 2 and 3 completed)	Mathias Goeckede
1.3	1/05/2018	3nd Draft (Sect. 4 completed)	Katrin Kohnert
1.4	07/05/2018	4th Draft (Sect 5 completed)	Francisco Navarro
1.5	15/05/2018	Consolidated draft	Andreas P. Ahlstrøm
2.0	31/05/2018	Final version	Donatella Zona

Approval	Date:	Sign.
X	31.05.2018	Coordinator

USED PERSON-MONTHS FOR THIS DELIVERABLE					
No	**Beneficiary**	**PM**	**No**	**Beneficiary**	**PM**
1	NERSC		**24**	Terradue	
2	UiB	**0.5**	**25**	GINR	
3	IMR		**26**	UNEXE	**7**
4	MISU		**27**	NIVA	
5	AWI		**28**	CNRS	
6	IOPAN		**29**	U Helsinki	**1.4**
7	DTU	**6**	**30**	GFZ	**6**
8	AU		**31**	ARMINE	
9	GEUS	**1**	**32**	IGPAN	**1**
10	FMI	**3.6**	**33**	U SLASKI	**1.1**
11	UNIS		**34**	BSC	
12	NORDECO		**35**	DNV GL	
13	SMHI	**2**	**36**	RIHMI-WDC	
14	USFD	**7**	**37**	NIERSC	
15	NUIM		**38**	WHOI	
16	IFREMER		**39**	SIO	
17	MPG	**7**	**40**	UAF	
18	EUROGOOS		**41**	U Laval	
19	EUROCEAN		**42**	ONC	
20	UPM	**4**	**43**	NMEFC	
21	UB		**44**	RADI	
22	UHAM		**45**	KOPRI	
23	NORUT	**x**	**46**	NIPR	
			47	PRIC	

x = contribution to the deliverable

DISSEMINATION LEVEL		
PU	Public, fully open	X
CO	Confidential, restricted under conditions set out in Model Grant Agreement	
CI	Classified, information as referred to in Commission Decision 2001/844/EC	

EXECUTIVE SUMMARY
This document describes the critical knowledge gaps and suggests future research directions. This document is intended to: – define the current gaps in knowledge in critical field investigating the impact of climate change on terrestrial and cryosphere systems – suggest the direction that future studies should undertake to address these gaps

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1. Introduction

This report is prepared to assess the existing ocean observing systems, and is based on responses from INTAROS partners to a set of questionnaires. The survey addresses Arctic in-situ and satellite-based observations of the ocean, atmosphere and terrestrial parameters retrieved through established networks/observing systems as well as individual measurement campaigns and projects. In this report we analyse the responses covering the terrestrial and cryospheric environment.

1.1. Link to previous assessments

Assessments of Arctic observations have recently been carried out in the framework of the EU project EU-PolarNet and of the ESA project “Polaris: Next Generation Observing Systems for the Polar Regions”. Other assessments that focused on European data collections addressed also some datasets covering the Arctic region. This is the case for data maturity evaluations undertaken in the framework of CORE-CLIMAX and GAIA-CLIM projects. In the following paragraphs, these previous assessments are described and their results summarized.

The deliverable D2.25 of the CORE-CLIMAX FP7 project (Schulz et al., 2015) reported the outcome of an assessment of Europe’s capacity to provide climate data records for Essential Climate Variables (ECV) as defined by the Global Climate Observing System (GCOS). One of the scope of the assessment was to support the establishment of the Copernicus Climate Change Service. The assessment addressed satellite and in situ climate data records (mostly gridded processed data) as well as weather prediction model-based reanalysis output, and was based on the System Maturity Matrix (SMM) method developed by the CORE-CLIMAX project. The applicability of the SMM for capacity assessment was well demonstrated by the 37 data records assessed. Among them are satellite terrestrial/cryospheric products such as the ESA Greenhouse gases (GHG)-CCI datasets, the Cryoland Glacier product, the METEOSAT, GEOV1, and CLARA-A1-SAL Surface Albedo products, the GEOV1 Leaf Area index (LAI) and fAPAR, the ESA-CCI Soil Moisture, the GlobSnow Snow Extent, and the H-SAF and LSA-SAF daily snow cover products. All these satellite products cover also the Arctic region.

Concerning other satellite data, selected terrestrial and cryospheric products were addressed in the Polar View report on Gaps and Impact Analysis of the existing EO missions in Polar Regions (Polar View, 2016). The study focused mainly on cryospheric products, and gaps were identified with respect to the applicability of different groups of EO sensors to provide information on the addressed themes (River and Lake ice, Ice Sheet, Glaciers, Snow, Icebergs, Permafrost, etc., see Fig 20 in Polar View, 2016). The final recommendation that emerged from the gap analysis was that future mission planning should focus on making optimum use of existing, rather than development of new, sensor technology.

Furthermore, the Polar View report identified the primary gaps in existing environmental information in meeting user needs on the basis of literature review and consultations with representatives and user organizations (Table 5 in Polar View, 2016). The assessed data characteristics were spatial and temporal resolution, timeliness (the amount of delay between the data collection and its accessibility for subsequent use), data continuity, and coverage. The key environmental information gaps were divided into two groups: concerning Polar earth science, and concerning Polar operations. For Polar earth science, the identified key information gaps in the terrestrial cryosphere domain were Ice sheet mass balance and Snow cover, and the two parameters considered of most concern were “Extent” (of glacier, snow, iceberg, and permafrost) and "Surface structure/albedo" (of ice sheet, glacier, snow, permafrost, and land). For Polar operations, the identified key information gaps only concerned Sea ice. Finally, a gap analysis of the Polar data value chain was performed, addressing the following points: data discovery, data access, data integration, data platforms, and training. Deficiencies were found in all the listed aspects (see Table 7, Polar View, 2016).

A survey was made by the H2020 project EU-PolarNet to assess the data management of Polar observing systems. The 58 addressed observing systems operate in either the Arctic or Antarctic region. Although the evaluated Arctic observing systems are too few to derive a conclusive picture on the arctic data management, the results of the survey suggested that data interoperability would require the adoption of more advance data management practices, such as those developed for large multi-organizational system-of-systems.

These previous assessments form the foundation for the present and companion INTAROS reports on the existing observing capacity and gaps in the Arctic. To ensure continuity and comparability with the CORE-CLIMAX and GAIA-CLIM assessments, the terrestrial and cryospheric satellite products and the in situ observing systems were assessed in INTAROS using the SMM method developed by the CORE-CLIMAX and GAIA-CLIM projects, respectively. As most of the in situ observing systems measure a large number of different variables that have different characteristics in accuracy, documentation, etc., the data collections measured by the observing systems were separately assessed. Additionally, in situ and satellite data characteristics such as data coverage, resolution, timeliness, and accuracy were assessed with respect to user defined (and observing system-specific) requirements for most in situ data, as well as WMO requirements defined in the OSCAR database (https://www.wmo-sat.info/oscar/requirements) for some in situ and all satellite data.

1.2. The INTAROS survey and questionnaire

The existing observing systems are evaluated based on a standardized survey among the INTAROS partners. The survey is undertaken via three questionnaires (Questionnaires A, B and C)(*).

The structure of the three questionnaires is defined as follows:

Questionnaire A: Existing Arctic In situ Observing Systems.

Section 1: General information on the observing system and the respondent
Section 2: Observed variables and potential environmental impact
Section 3: Sustainability of the observing system
Section 4: Data usage
Section 5: Data management

Questionnaire B: In situ data collections

Section 1: General information on the data collection and the respondent
Section 2: Sustainability of the data collection
Section 3: Data usage
Section 4: Data management
Section 5: Data coverage, resolution, timeliness and format
Section 6: Uncertainty characterization
Section 7: Metadata specification and documentation

Questionnaire C. Satellite Products

Section 1: General information on the data products and the respondent
Section 2: Data management
Section 3: Data coverage, resolution, timeliness and format
Section 4: Uncertainty characterization
Section 5: Metadata specification and documentation

More information about the questionnaires are found at https://intaros.nersc.no/node/651.

1.3.Definition of the components of an in situ observing system

An **in-situ observing system** consists of a data collection component (infrastructure) and a data management component (e-infrastructure). The data collection component is comprised of multiple sensors either belonging to a common fixed platform (such as cabled system, sea floor installation, mooring), which can be a single unit or a collection of units forming a network, or installed on a temporary platform (ship, aircraft, gliders, floats, ice buoys). The data collection component stores the datasets internally or transmits them to the data management component. The data management component includes hardware and software for data repository, the data processing, data discovery and visualization services. The management can be centralized in a single institution or distributed among several national institutions, which have agreed on common standards for the data and metadata formats, documentation and management. An observing system can be multidisciplinary or focused on a specific discipline, and it serves a clearly identified scientific or operational purpose.

The different terrestrial/cryospheric in situ observation systems are assessed through the responses to QA. The results from the QA are presented in **Section 4.1**.

1.4.In situ data collections

An **in-situ data collection** is defined as a collection of data, or measurement series, that have common characteristics in terms of quality, resolution, and coverage. In most cases, the observation platform and its instrumentation used to collect the data determines the characteristics of the collection. In the present survey, the instruments applied to collect the data range from manual tools to fully automatized sensors, while the observation platform can be moving, drifting or fixed. Thus, a data collection generally includes all the variables measured with a single instrument. In situ data collections also include derived data products which result from processing of individual measurements or composition of multiple measurements. In situ data collections can be surface-, subsurface-, and air-borne.

Each observing system in QA can produce a number of data collections. In QB single parameter datasets are assessed with respect to data characteristics such as coverage, quality, and resolution. The results from the QB are presented in **Section 4.2**. In general the data collection in QB belongs to an observing system, but not always, some data sets come from research campaigns.

We address different kind of data collections:
1) data from established ocean in situ networks, having regional spatial coverage and variable temporal coverage,
2) data from single stations, having local areal coverage and variable temporal coverage,

3) data from field campaigns (ship-, aircraft-, UAVs), with limited temporal coverage and from point to regional spatial coverage.

Most of the information required for the evaluation of the data collections is collected through QB.

1.5.Satellite products

Due to their different characteristics, the Earth Observations (EO) products are separately assessed in **Section 4.3**. The assessment has its foundation on the Gaps and Impact Analysis Report done by Polar View (2016) (REF), and further deepens the analysis of gaps in spatial and temporal resolution, uncertainty, timeliness, and data value chain for selected EO products. The information needed for this assessment is collected through Questionnaire C.

1.6.Scope of the assessment

Observing system. The current assessment is limited to the Questionnaire A (QA) responses provided by the INTAROS consortium. This means that several important ocean observing systems are not included such the Nansen and Amundsen Basins Observational Systems (NABOS) or the moorings in the Baffin Bay Observatory. Questionnaire A is now open for external partners to fill in, and the opening has been announced widely through AMAP and the projects within the EU Arctic Cluster.

Data Collections. Questionnaire B (QB) was designed to evaluate important data to be included in the iAOS for use in applications for different Stakeholders (WP 6). Those datasets will be listed in the data catalogue to be incorporatedin the data portal.

Satellite products. This report does not intend to assess all satellite products available from the Earth Observation (EO) community. This is because assessment of satellite products are carried out by other projects such as Polar view (2016). Only EO data useful for the stakeholder applications in INTAROS has been selected and assessed through the Questionnaire C (QC).

1.7.Organization of the report

In Section 2 we describe each of the assessed in situ observing systems, as well as the assessed in situ and EO datasets. In Section 3 the set of requirements used in the assessment is provided.

For a comprehensive evaluation of the observational data, the assessment addresses general aspects of the in situ observing systems (Section 4.1), specific aspects of the single in situ data collections (Section 4.2), and the most relevant aspects of the satellite products (Section 4.3).

The gaps in the in situ observing systems are identified in terms of data availability and spatial distribution (Section 4.1.2-4.1.3.), system uncertainty (Section 4.1.4.), sustainability of the observing system (Section 4.1.5.), data usage (Section 4.1.6), and data management (Section 4.1.7). Most of the needed information to perform this gap analyses is collected via the Questionnaire A of the WP2 survey.

2. Data description

This section includes the description of the work done to format the data and to characterize them (determining coverage, resolution, uncertainty, etc.) in order to allow their thorough assessment.

2.1. UiB and GEUS

2.1.1. Seismological monitoring in the Arctic

As a contribution to D2.7, a catalogue of seismological monitoring capabilities is developed for the Arctic region, including location of seismic monitoring stations, their call code and network code. The catalogue covers the area north of the Arctic Circle (65.563N) and covers the 50-year period 1965 – 2014 (2014 is the last full year reviewed by the ISC).

The catalogue is compiled by searching ISC, GFZ and IRIS databases for stations North of the Arctic Circle. For each station the time period of operation is noted, including if currently open. A note is also made to identify if data from the station is freely available or if restricted, in which case a note is made of when the restriction period ends (if known).

Status at the end of February 2018 in the merged list exists in an excel worksheet, and checking of the Russian stations is in progress. Most (but not all) non-Russian stations are checked. Maps of all stations and of currently active and open stations are also available (Fig. 1).

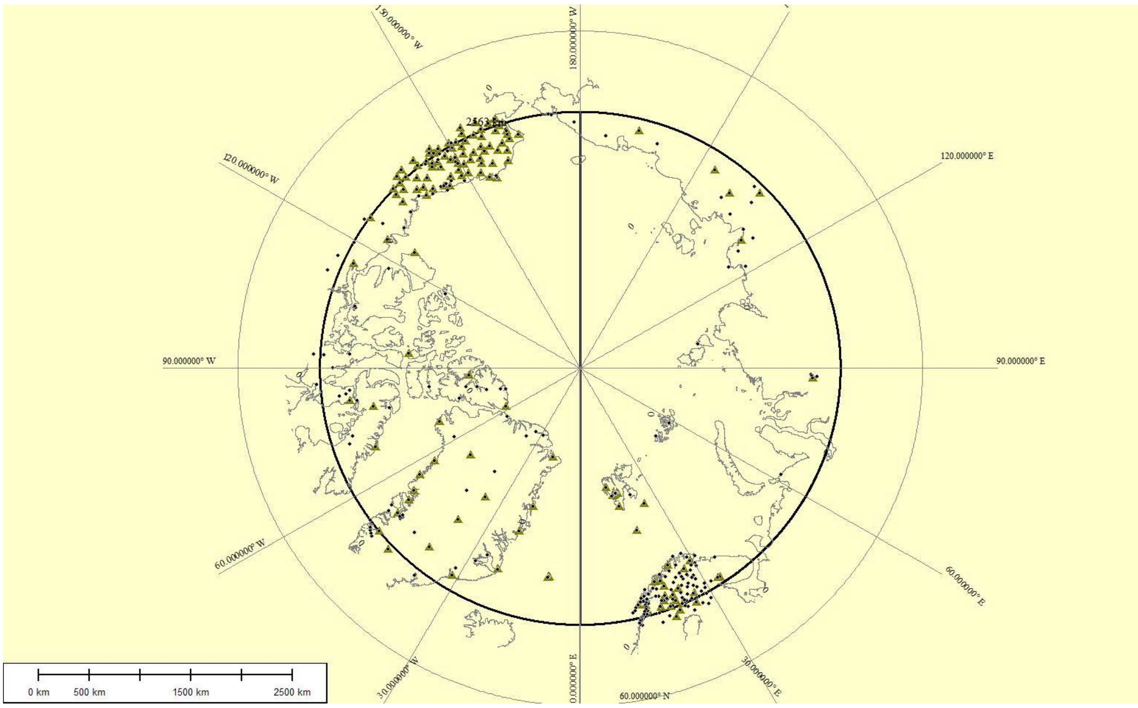

Figure 1. Map of seismic stations in the Arctic (black dots). Stations which are currently active are marked as green triangles.

2.1.2 Detection threshold of earthquakes in the Arctic region

In this section, an evaluation of the detection threshold of earthquakes in the Arctic region is presented. Its aim is to provide information on the effects the monitoring coverage has on the lower limit to which small earthquakes can be detected across the Arctic region.

The magnitude of an earthquake determines to what distance it can be observed: larger magnitude means larger distance. Furthermore, to establish the location of an earthquake it has to be detected by several seismographs. The evaluation is based on the location of seismographs in the region that are operated with the purpose of earthquake monitoring and an assumption on the magnitude-distance relationship, and with suggestions for future locations.

Since the location of seismograph is a varying parameter over time, estimations are performed using different seismograph location configurations and the access to data online, in order to illustrate the limitations due to limited data access. Furthermore, the possibilities of including OBSs (ocean bottom seismometers) in earthquake monitoring scenarios including different OBS installation setups are included. The magnitude-distance relationship applied is adopted from an evaluation for Norway (Demuth et al. 2016) that gives a relation based on the Richter scale:

$$ML(d)=0.5 + 0.004d$$

where, at distance d (in km), a Richter scale magnitude M_L can be detected.

The evaluation includes different uncertainties, such as variations in the ambient noise level e.g. seismic noise generated by seasonal variations in wind or ocean waves, which might lower the detection probability or variations in the seismic wave attenuation around individual seismic stations that might bias the observed earthquake magnitude. These effects are not insignificant. For Norway, Demuth et al. (2016) finds that for an increase in noise levels of 10 dB, the detectability of earthquakes decreases by a local magnitude of 0.5 and that detectability of regional and local events of individual stations can vary by two units of magnitude. For Greenland, Gregersen (1982) finds that magnitudes should be corrected by 0.7 at some stations and some stations should not be included in magnitude computation for earthquakes that occur at specific azimuths.

The application of the magnitude-distance relationship for Norway also includes an additional uncertainty since the relationship is based on magnitudes estimated from the size of the seismic Lg wave, but for earthquake-station paths that cross the Arctic oceanic plate the amplitude of the Lg waves are often blocked or ineffectively propagated (Chiu and Snyder, 2015). A solution to the Lg blocking could be to use the amplitude of the Pn wave, as suggested by e.g. Kim and Ottemöller (2017).

Figures 2-7 illustrate the detection threshold based on a synthetic determination based on the configuration of the location of seismograph stations in the region. However, since earthquakes of larger magnitude are likely to be detected by seismograph stations beyond the Arctic region these stations will determine a global magnitude detection threshold that also includes the Arctic region. For an earthquake stronger than magnitude 4.5 one expects that it is most likely to be detected by the global net of seismographs. The ISC (2015, p.108) reports a magnitude of completeness of 3.9 using the body wave magnitude scale mb, but given the relationship between mb and moment magnitude (ISC, 2015 fig. 8.28) at lower magnitudes, 4.5 is a conservative estimate of the upper magnitude limit of the window of undetected earthquakes. Hence the interpretation of the detection threshold figures below is that any earthquake with a magnitude smaller than the magnitude given in the figures will not be detected, if this value is smaller than magnitude 4.5.

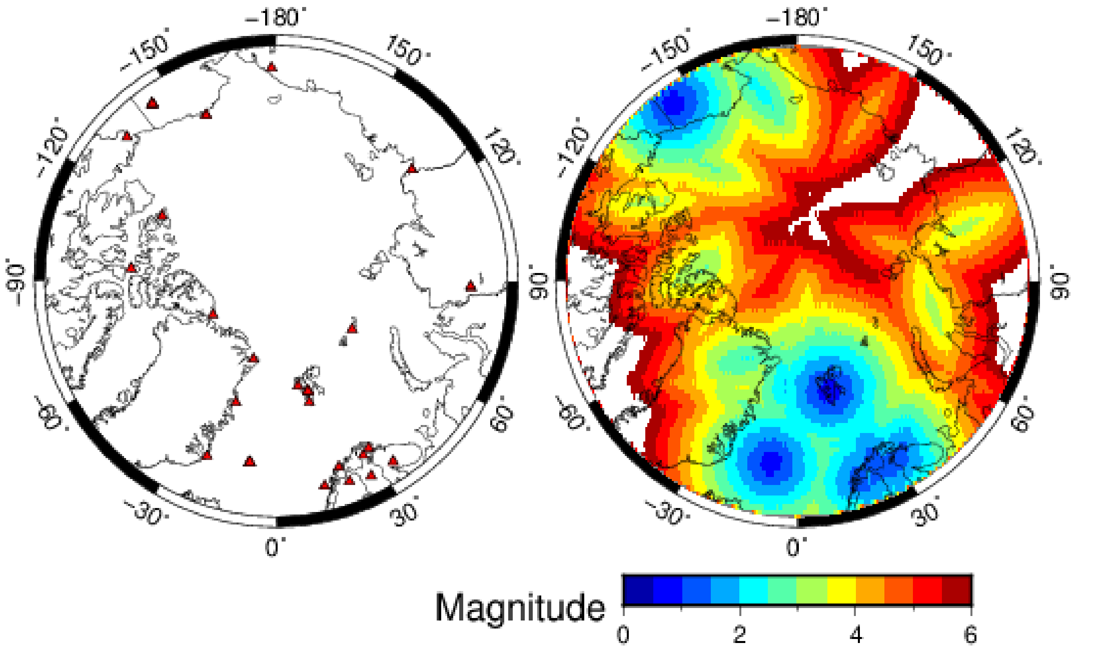

Figure 2. Earthquake monitoring stations active in 1995 (red triangles in left plot) and the estimated magnitude threshold (right plot); the threshold in white areas is above 6.

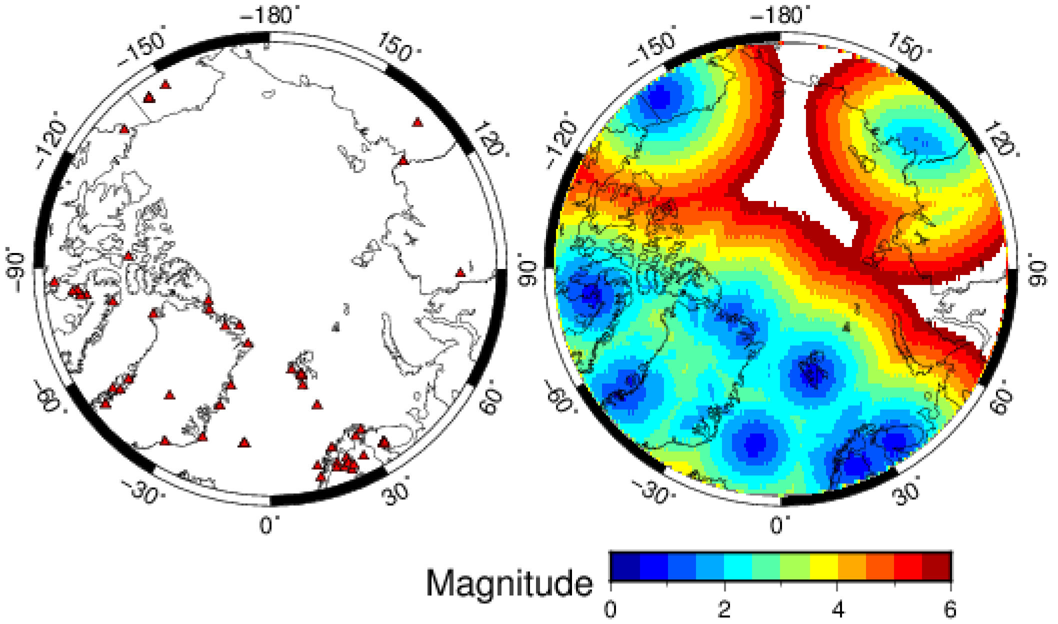

Figure 3. Earthquake monitoring stations active in 2005 (red triangles in left plot) and the estimated magnitude threshold (right plot); the threshold in white areas is above 6.

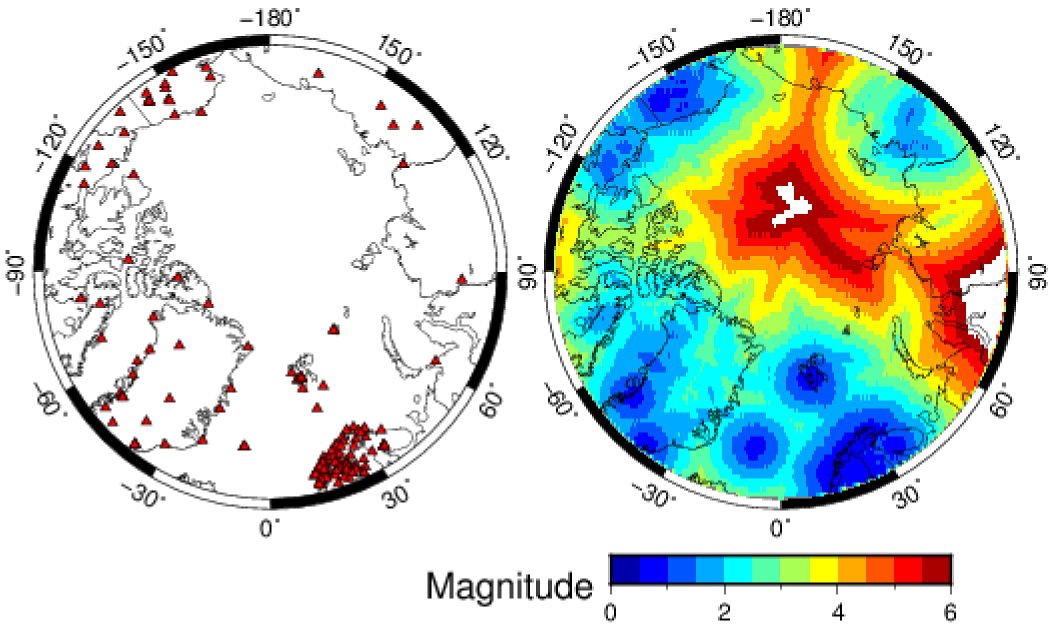

Figure 4. Earthquake monitoring stations active in 2015 (red triangles in left plot) and the estimated magnitude threshold (right plot); the threshold in white areas is above 6.

To illustrate the improvement in earthquake monitoring in the Arctic region since 1995, three maps showing the station location and the magnitude threshold for the years 1995, 2005 and 2015 are shown in Figs. 2, 3, and 4, respectively. The improvement from 1995 to 2005 is most prominent in east Canada and in West and North Greenland. From 2005 to 2015 the increasing number of stations in Alaska improved the detection threshold, but the removal of temporary stations in North Greenland and East Canada lowered the threshold.

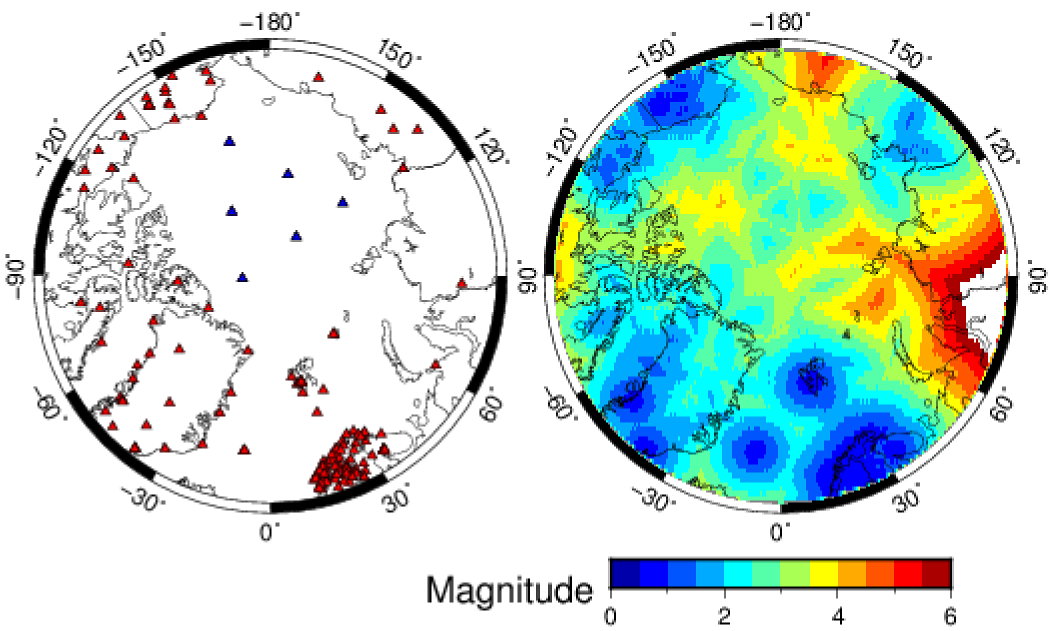

Figure 5. Earthquake monitoring stations active in year 2015 and suggested optimal locations for six OBS instruments (red and blue triangles, respectively) (left plot) together with the expected magnitude threshold (right plot); the threshold in white areas is above 6.

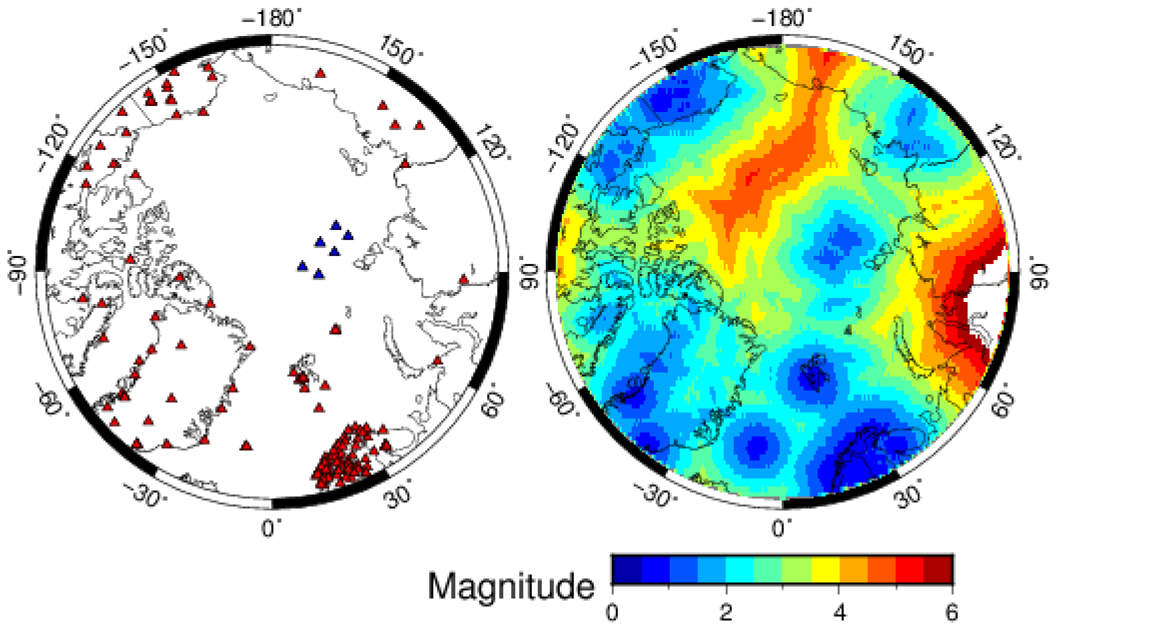

Figure 6. Earthquake monitoring stations active in year 2015 and suggested locations for six OBS instruments (red and blue triangles, respectively) (left plot) together with the expected magnitude threshold (right plot); the threshold in white areas is above 6.

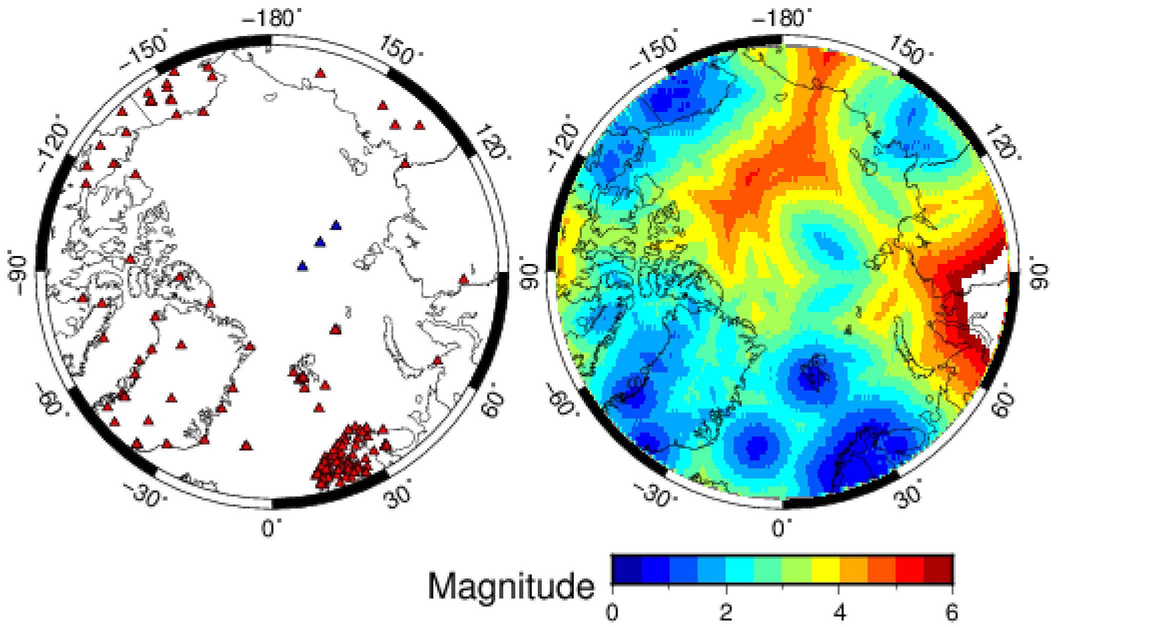

Figure 7. Earthquake monitoring stations active in year 2015 and suggested locations for three OBS instruments (red and blue triangles, respectively) (left plot) together with the expected magnitude threshold (right plot); the threshold in white areas is above 6.

To illustrate how OBS instruments deployed on the Arctic Ocean sea floor would improve the detection threshold for earthquakes in the region three simulations are presented (Fig. 5-7). In all the three, year 2015 station configuration is used as background information. In the first simulation the expected detection threshold is estimated for a setup of six OBS instruments placed in a near optimal configuration in the Arctic Ocean (Fig. 5). This configuration would give a detection threshold between magnitude 2 and 4 in most of the Arctic Ocean. However, to maintain such a configuration, including yearly visits, would require large resources and icebreakers that can pass all kind of ice situations. The two simulations presented in Figs. 6 and 7 show more realistic configurations within the near future, since the suggested location of the OBS's are near the Gakkel Ridge, the northern part of the geological spreading zone between the tectonic plates of North America and Eurasia. This configuration is simpler, which makes access to the instruments easier and, since the area often is exploited for research purposes, access by an icebreaker is more likely.

2.2. DTU

2.2.1 The Greenland GPS Network (GNET)

The Greenland GPS Network (GNET) (Fig. 8) is constructed to measure the impact of climate cycles and climate change on ice mass balance in the world's second largest ice sheet. The primary objective of GNET is to "weigh" the Greenland ice sheet by measuring the earth's instantaneous elastic response to contemporary changes in ice mass. However, merging GPS data with satellite gravity from Gravity Recovery and Climate Experiment (GRACE) will provide a new means to measure high resolution ice-sheet-wide mass changes of the Greenland ice sheet.

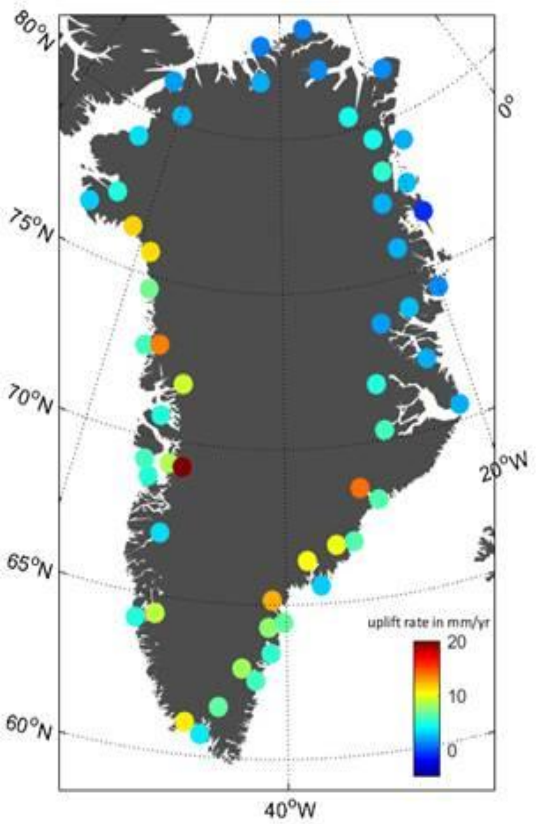

Figure 8. Location of GPS stations and observed elastic uplift rate in mm/yr, due to present-day ice mass loss.

To estimate site coordinates, we followed the procedure of Khan et al. (2010). We used the GIPSY OASIS 6.4 software package developed at the Jet Propulsion Laboratory (JPL). We used JPL final orbit products, which include satellite orbits, satellite clock parameters, and Earth orientation parameters. The orbit products took the satellite antenna phase center offsets into account. Receiver clock parameters were modeled, and the atmospheric delay parameters were modeled using the Vienna Mapping Function 1 (VMF1), with VMF1 grid nominals. Corrections were applied to remove the solid Earth tide and ocean tidal loading. The amplitudes and phases of the main ocean tidal loading terms were calculated using the automatic loading provider (http://holt.oso.chalmers.se/loading) applied to the FES2004 ocean tide model, including correction for center of mass motion of Earth due to the ocean tides. The site coordinates were computed in the IGS08 frame. Figure 9 shows the time-series of vertical displacements for each GNET station.

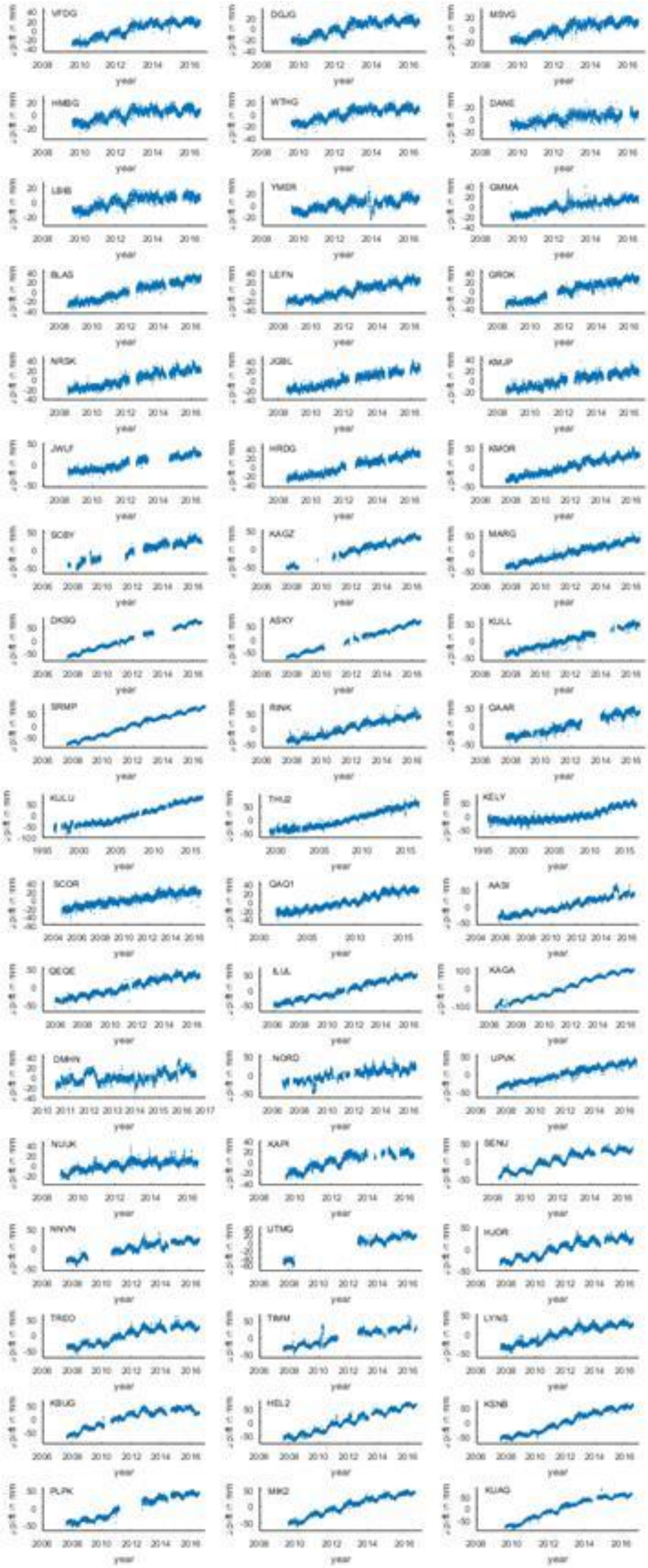

Figure 9. Vertical displacement for each GNET station

In general, most stations have continues data without any major data gap, and are categorized “green” in Fig. 10. Stations categorized “yellow” have minor gaps, while stations categorized as “orange” have large gaps and may be problematic in our attempt to merge GPS with GRACE data.

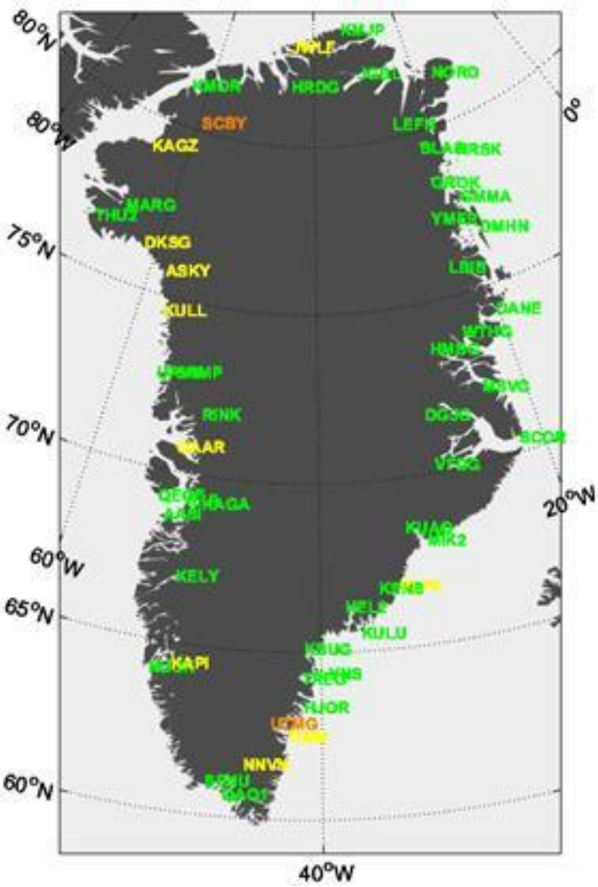

Figure 10. Spatial assessment of GNET sites. Green=good, yellow=minor gaps, orange=potential serious gaps.

Out of in total 54 assessed timeseries, we find 2 potential problematic time series with large gaps. However, from 2012 onward, all stations show continuous time series without any major gaps and useable for further analyses and ice sheet mass change monitoring.

2.2.2 The Gravity Recovery and Climate Experiment (GRACE) satellite mission

The GRACE mission allows for direct estimates of ice-sheet-wide mass variability, through determining the effects of that mass on the Earth’s gravity field. Since its launch in March 2002, GRACE has been measuring changes in the range between two satellites that are in identical near-polar orbits (the injection altitude was 500 km), about 220 km apart. The changes in range are used to construct monthly solutions for the gravity field at the Earth’s surface. Solutions are generated, for example, at the Center for Space Research (CSR) at the University of Texas (Tapley et al., 2004), the Jet Propulsion Laboratory (JPL) at the California Institute of Technology (Landerer et al., 2012) and the Deutsches GeoForschungsZentrum (GFZ) at Helmholtz Centre Postdam (Kusche et al., 2009). The gravity fields consist of spherical harmonic (Stokes) coefficients, C_{lm} and S_{lm}, where l and m denote the degree and order of the harmonic coefficients, respectively; though most users replace the GRACE C_{20} coefficients with C_{20} estimates inferred from satellite laser ranging (Cheng and Tapley, 2004).

The GRACE gravity solutions allow users to determine monthly mass fluctuations averaged over scales of a few hundred km and greater. Mass variability from individual glaciers, though, cannot be resolved. The contributions from all glaciers within a region are automatically included in a regional estimate, but it is not possible to determine how much each glacier contributed (Velicogna at al., 2014). Unlike other methods, GRACE provides a direct estimate of mass balance, without requiring any intermediate assumptions (other than Newton's Law of Gravity). However, the GRACE gravity fields represent the total gravity variability from all geophysical sources, and cannot distinguish between contributions from ice sheet mass, and those from such things as mass variations within the atmosphere, ocean, and liquid water storage on land; or from signals associated with mass variability in the solid Earth: e.g. episodic (earthquake) processes, and glacial isostatic adjustment (the viscoelastic response of the solid Earth to glacial unloading over the last several thousand years) (Sutterley et al., 2014). For Greenland, none of these other sources of gravity is likely to be a serious problem. The GRACE centers use model output to remove atmospheric and oceanic signals before constructing the monthly gravity fields. Greenland is far enough from other land areas that the effects of liquid land water storage do not cause appreciable contamination of the Greenland results. And, Greenland and the surrounding region do not experience earthquakes that are large enough to significantly affect the Greenland mass estimates. The GIA signal is potentially more of an issue. Since it is linear and cannot be separated from a linear trend in present-day ice mass, it should be independently modelled and removed. However, existing GIA models suggest that this correction is rather small for Greenland, about -7±19 Gt/yr (Velicogna and Wahr, 2006).

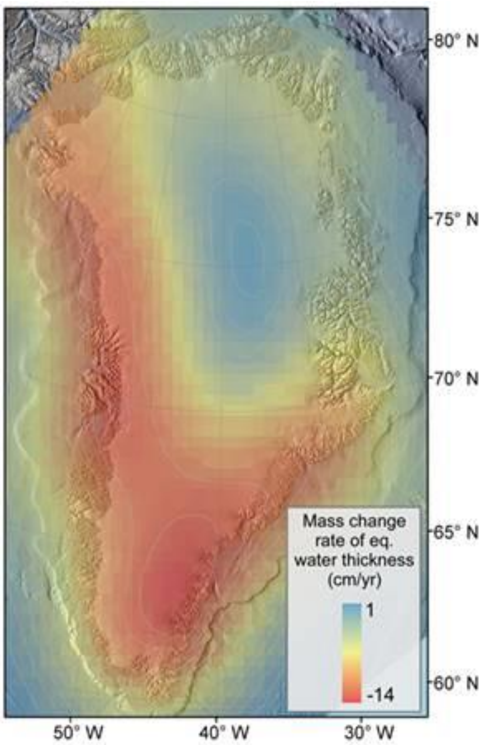

Figure 11. Average April 2002 to June 2014 mass change rate of the Greenland Ice Sheet extracted from GRACE, in units of centimetres per year of equivalent water thickness.

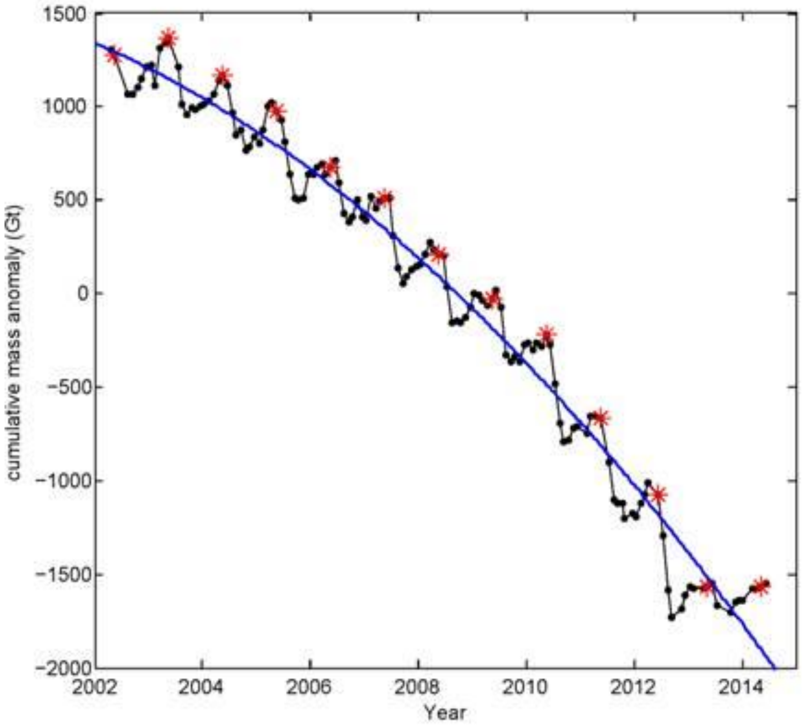

Figure 12: Time series of the cumulative ice sheet-wide mass anomaly of the GrIS extracted from GRACE, in Gigatonnes. The red asterisks denote June values (or May values, for years when June is missing), and best-fitting trend quadratic trend (blue).

Figure 11 shows the average rate of mass change across the GrIS between April, 2002 and July, 2014, determined from the CSR GRACE fields. The GRACE C_{20} gravity coefficients are replaced with those estimated from satellite laser ranging (Cheng and Tapley, 2004). Degree-one coefficients are also included, computed as described by Swenson et al. (2008). The method described in Wahr et al. (1998) is used to transform the gravity coefficients into surface mass coefficients. Those coefficients are used to compute surface mass on a 0.5 x 0.5 degree grid, smoothed with a Gaussian smoothing function with a 250 km half-width. Figure 12 shows the time series of the total mass change for the GrIS, estimated from GRACE monthly mass solutions for the period from April, 2002 to June, 2014.

2.3. GEUS

2.3.1 Programme for Monitoring of the Greenland Ice Sheet (PROMICE)

The Programme for Monitoring of the Greenland Ice Sheet (PROMICE) is an on-going effort to monitor changes in the mass budget of the Greenland Ice Sheet and is operated by the Geological Survey of Denmark and Greenland (GEUS) in collaboration with the National Space Institute (DTU Space) and the Greenland Survey (Asiaq) started in 2007.

A central part of PROMICE is the network of presently 22 automatic weather stations (AWS) (Fig. 13) situated in the ablation zone of the Greenland ice sheet. Combining these with airborne surveys of ice thickness and mapping of ice velocities makes it possible to estimate the mass loss of the Greenland ice sheet. Also mapping of individual glaciers and ice caps surrounding the ice sheet is done to assess the mass loss. The PROMICE data can be used directly as indicators of climate change, becoming more and more valuable as the monitoring period increases. Furthermore the programme contributes through observations to process-oriented studies to understand the mass loss as well as validation efforts to improve ice sheet models and future predictions.

PROMICE is committed to maintaining an accessible, safe and thoroughly documented database for storing and disseminating the data free of charge to the climate research community.

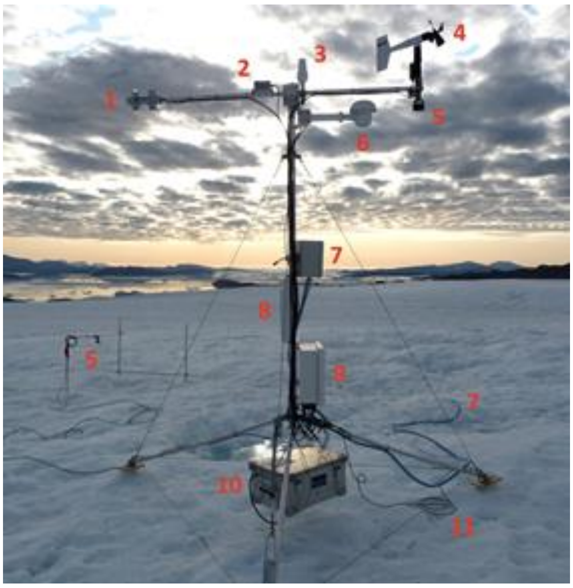

Figure 13. PROMICE automatic weather station UPE_L. 1: radiometer. 2: inclinometer. 3: satellite antenna. 4: anemometer. 5: sonic rangers. 6: thermometer and hygrometer. 7: pressure transducer. 8: solar panel. 9: data logger, barometer and GPS. 10: battery box with 4 × 28 Ah batteries. 11: 8-level thermistor string.

The PROMICE station network currently consists of 22 automatic weather stations (AWS), of which 19 are on the ice sheet proper. The stations are primarily distributed over eight melt regions of the Greenland ice sheet (Fig. 14). In each melt region, one station is located in the lower ablation zone close to the margin, and one or two in the middle/upper ablation zone, to obtain elevation gradients of measured variables. Exceptions are KAN_U and KPC_U (located in the lower accumulation area), EGP (in the upper accumulation area), MIT and NUK_K (on independent glaciers), and KAN_B (on tundra at one kilometer from the ice sheet margin). The AWS's measure the meteorological variables: temperature, pressure, humidity, wind speed, and the downward and upward components of solar (shortwave) and terrestrial (longwave) radiation. They also record temperature profiles in the upper 10 m of ice, GPS-derived location and diagnostic parameters such as station tilt, which is crucial for interpreting solar radiation measurements. A GEUS-developed pressure transducer and two sonic rangers measure snow and surface height change due to ablation and accumulation.

Measurements are taken at a ten-minute time interval, with all data stored locally awaiting collection during maintenance visits. Hourly averages of the most transient variables are transmitted via Iridium satellite link between days 100 and 300 of each year, while a selection of the remaining variables is transmitted at six-hour intervals. Transmissions have a lower, daily frequency in the winter period to save battery power and transmission costs. All data and metadata including sensor specifications are archived in the PROMICE database and made freely available for display and download at www.promice.dk.

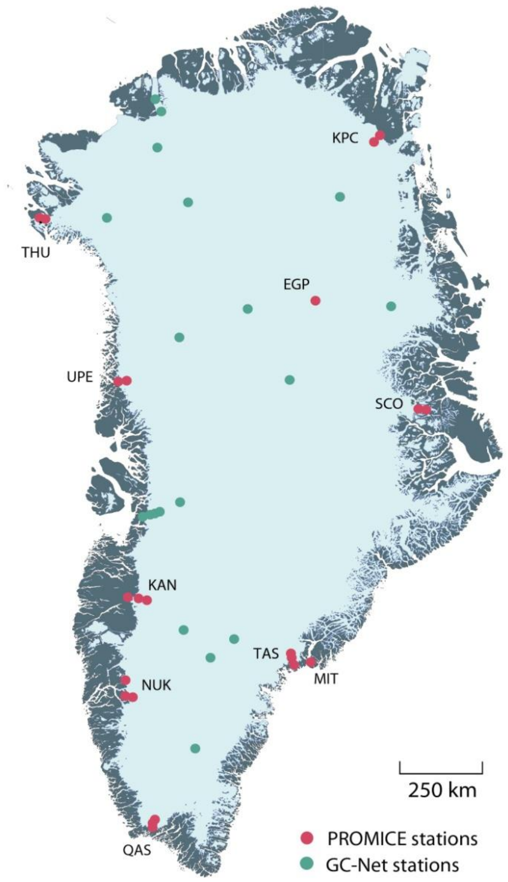

Figure 14. Location of PROMICE and GC-Net automatic weather stations. Note that a number of these stations have been discontinued (primarily GC-Net stations).

The spatial coverage is largely determined by what is feasible from a logistical/economic point of view, while maintaining an icesheet-wide coverage. With the exception of the KPC stations in Northeast Greenland, all stations can be reached by helicopter from a heliport without making use of additional fuel depots. This minimizes cost and environmental footprint, but also implies that coverage is sparser in Eastern and Northern Greenland. Spatial variability in meteorological parameters is also expected to be high in Southeast Greenland, which experiences severe weather with heavy precipitation and extreme winds. Additional stations on the ice sheet margin between TAS and QAS would alleviate this problem, but the logistical cost as well as the high maintenance frequency expected precludes this location given the current budgetary constraints.

The temporal coverage of the stations is mainly a concern with respect to the data transmitted, where the winter transmission frequency is only daily. The PROMICE team is currently testing alternative instrument/power solutions to enable hourly transmissions throughout the winter in support of near real-time applications. Observations are stored locally in the logger every ten minutes and this more complete time series becomes available through the PROMICE database after station visits.

For an overview of the data coverage over the PROMICE period (since 2007) the air temperature measurement was chosen as an indicator and shown in Fig. 15. Overall the stations have been working 92% of the time using this metric. The detailed data coverage depends on each instrument, which may experience downtime irrespective of the general station performance. As an example, Fig. 16 illustrate the time series of various variable at a single station.

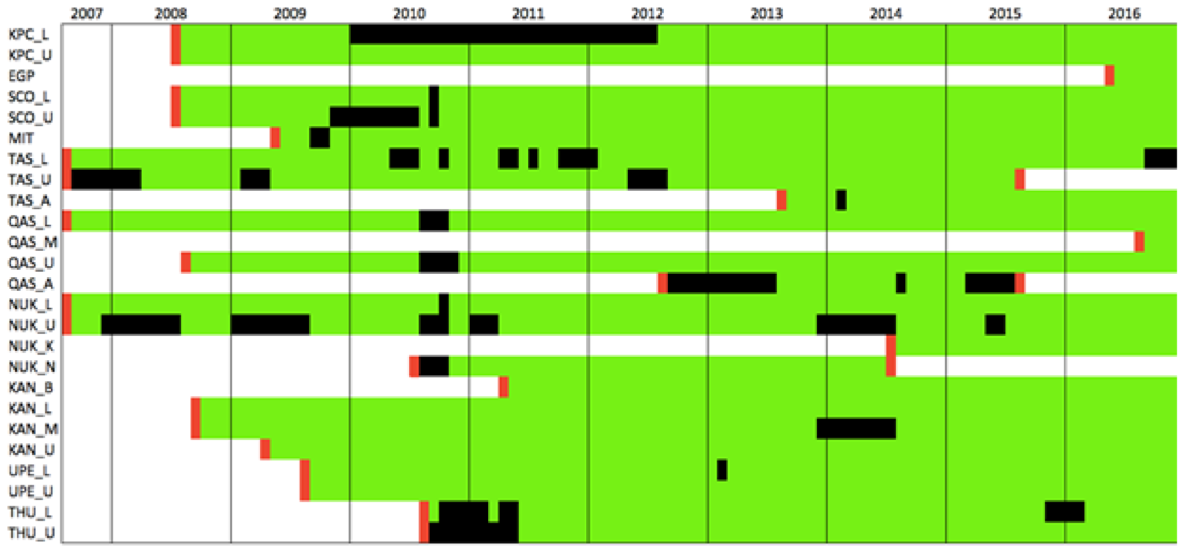

Figure 15. Air temperature measurement coverage (92% total) for all PROMICE weather stations in green. Red markers indicate the installation/removal of the stations. Data gaps are indicated in black.

The remaining issue in terms of coverage, apart from the spatial and temporal dimension, is the parameters measured. The automatic stations are situated in the melt zone of the Greenland Ice Sheet which experiences extreme and severe weather conditions frequently. As the ice surface continuously melts away and is simultaneously transported towards the ice margin due to ice flow, the stations are designed as tripods standing on the changing surface (see Fig. 13). The free-floating tripod design, the weather conditions and the power requirements, put constraints on what is feasible in terms of instrumentation. Our analysis points at precipitation as an important atmospheric parameter that is inadequately observed. Current observation of precipitation is limited to a sonic ranging device measuring the height of the snowpack. As most stations are in the ablation zone, the snow will have melted away at the time the station is visited. Some stations are only visited every second, third or even fourth year. Snow in the melt zone has a strong impact on surface melt as the (low albedo) ice only starts melting in earnest when the (higher albedo) snow is gone. Knowing the snow water equivalent gives a much better grasp of the physical processes at work and provides a data set to test models against. Another factor is the transition of precipitation from snow to rain which is happening over the Arctic region. Rain has the exact opposite effect on ice sheet surface mass balance compared to snow, as it provides a rich source of energy to remove existing snow and accelerate ice melt.

We are addressing these issues in INTAROS and PROMICE by adding selected new instruments at key stations. Specifically, we are installing instruments to measure the snow water equivalent (SWE) as well as rain gauges at lower stations in our more southerly station transects. Initially, these new systems will be kept as separately running systems so as not to jeopardize the core station operation. Over time, these new instruments will be integrated into the standard station set-up and established at all the stations where these parameters are relevant.

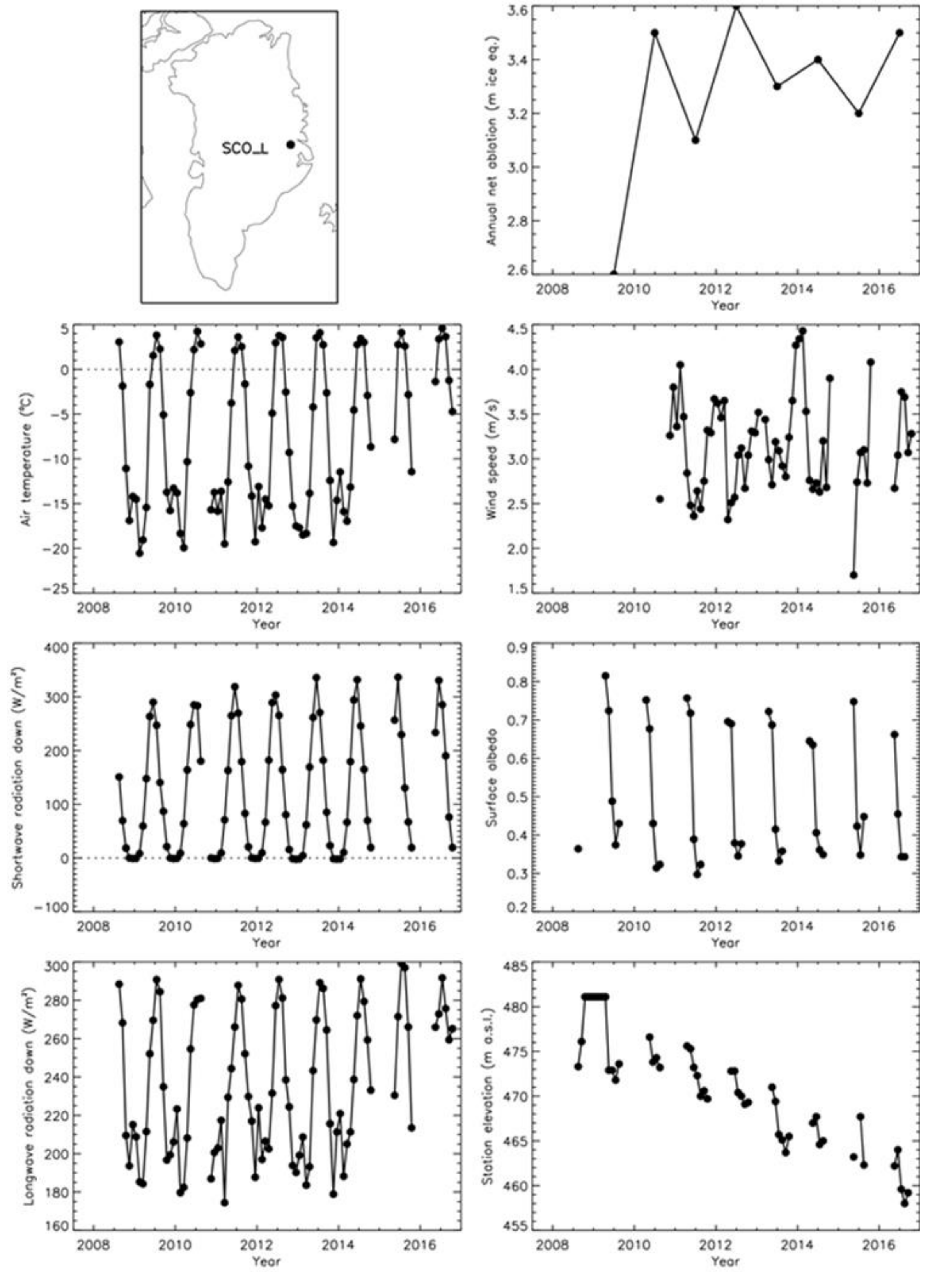

Figure 16. Example of monthly mean data from the PROMICE station SCO-L which is situated on Violin Gletsjer, an outlet glacier from the Greenland Ice Sheet near Scoresbysund fjord in central East Greenland.

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2.4. FMI

2.4.1 Snow, precipitation and soil frost

Data sets related to seasonal snow cover and soil freeze/thaw processes from the Finnish Meteorological Institute's station in Sodankylä, Finland (67.367N, 26.629E) are described here. The data, among other measurements, are available through the web site http://litdb.fmi.fi/.

2.4.2 Soil frost stations

There are 18 distributed measurement stations dedicated for monitoring seasonal soil freezing and thawing located in the Finnish Lapland. 15 stations are located close to the FMI station in Sodankylä and 3 are farther north in tundra in the Saariselkä area. A map of the measurement stations is shown in Fig. 17. A typical station setup is shown in Fig. 18, and includes soil temperature and dielectric constant profiles in three different spots, one with sensors at -5, -10, -20, -40 and -80 cm depths and two with sensors at -5 and -10 cm. Measurement results for one station are shown in Fig. 19.

Two of the stations include snow temperature profile and an additional snow depth station for assessing the influence of snow conditions on soil freezing. The three stations in Saariselkä include additionally solar radiation measurements and standard weather stations to enable the use of the data in land surface model experiments (such data are available from the Sodankylä site from other existing sensors). The first seven stations were established in 2011, and a few new ones have been added every year. The stations are located in soils and environments typical to the area, covering all major land cover.

The 10-min average data are available from http://litdb.fmi.fi/distributed_stations.php in csv text files separately for each station. The site is not updated in real time, as the data first go through quality control.

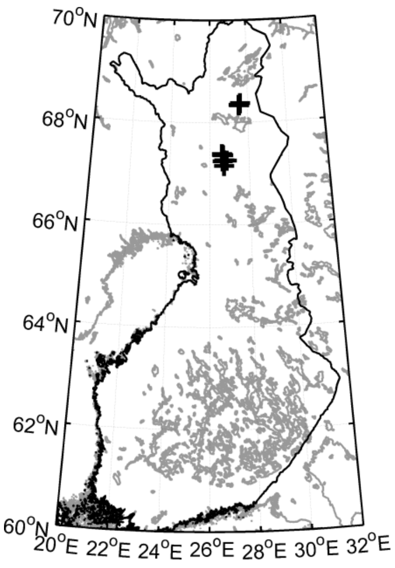

Figure 17. Map of soil frost/snow stations.

Figure 18. Typical station set-up with soil sensors in the ground and a snow temperature profile.

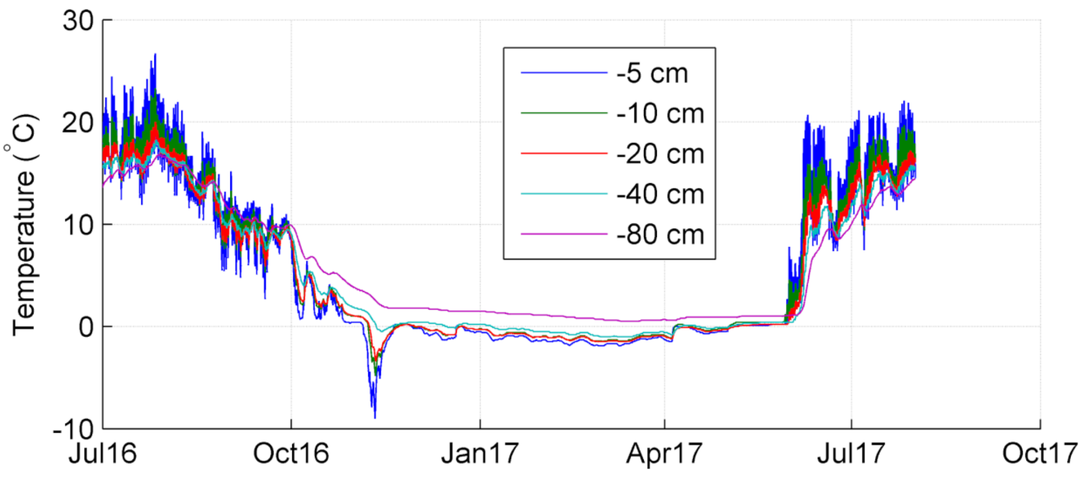

Figure 19. Soil temperatures measured at one station during winter 2016-2017.

2.4.3 Snow depth and meteorological variables from automated weather stations

Precipitation, air temperature and snow depth, among various other meteorological parameters, are measured by an automatic weather station. The 10-min average values since 2006 (2008 for snow depth) from the Sodankylä station are available from http://litdb.fmi.fi/luo0015_data.php in csv text files. These data are the official meteorological measurements from Sodankylä station and go through an automated and manual quality control. The station is part of the network of around 400 measurement stations hosted nationally by FMI (~200 of which report snow depth)

Figure 20. Snow depth station in forest opening.

There are several additional simplified weather stations at the FMI Sodankylä site and surroundings, providing snow depth and air temperature measurements (Figure 20). The purpose of the stations is to provide information on snow height evolution on different types of land cover, complementary to the standard AWS. An example of the snow depth data from one of those stations is shown in Fig. 21. The 10-min average data are available from http://litdb.fmi.fi/ioa0003_data.php and http://litdb.fmi.fi/suo0003_data.php in csv text files separately for each station. The site is not updated in real time, as the data first go through quality control.

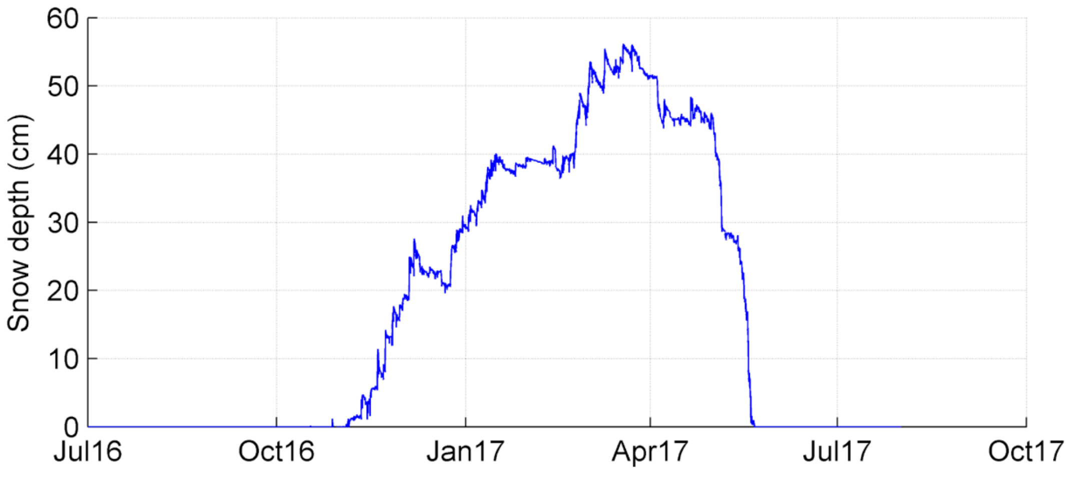

Figure 21. Snow depth during the winter of 2016-2017 at one station.

2.4.4 Snow scale SWE

A time series of SWE was measured using the Sommer SSG 1000 snow scale at one location (N67.361903, E26.633802). The 1-min average data are available from http://litdb.fmi.fi/ioa0011_data.php in csv text files.

The site is not updated in real time, as the data first go through quality control. SWE measurements are currently not provided by the standard AWS complement of FMI, and the snow scale represent the first initiative in Finland to do this operationally using an automated device.

2.4.5 Manual snow depth

A daily time series of manual snow depth measurements at the FMI Sodankylä site covers the time period from 1 Jan 1911 to 4 Feb 2008, when the measurement was automated (the AWS data set includes the automated measurements). Snow depth was recorded daily at 6 and 18 UTC against a fixed reference scale with 1 cm precision. The observations were manually entered into logbooks, from where it was manually collected for publication in national yearly statistics books, which have now been digitized. The data are available from http://litdb.fmi.fi/luo0016_data.php in csv text files. The data time series is shown in Fig. 22.

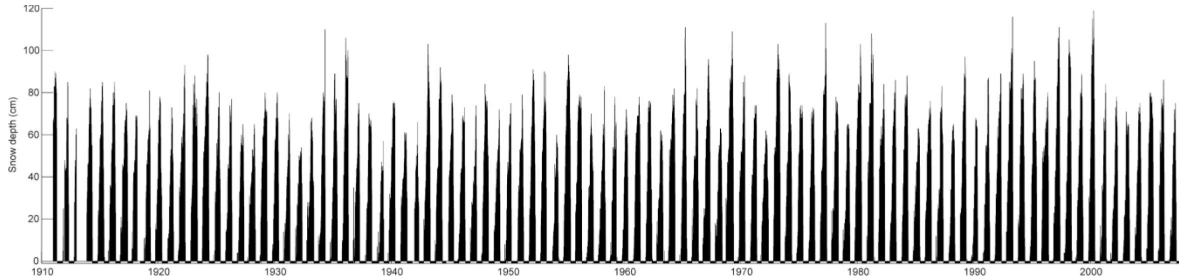

Figure 22. Daily snow depth time series.

2.4.6 EU ERA-CLIM2

A collection of in situ manual and automated (snow pillow) SWE observations from Finland, Canada and Russia collected in the ERA-CLIM-2 project. The dataset is an example of a concentrated effort to bring together in situ measured datasets on SWE from a variety of sources. Data coverage is shown on the map in Fig. 23. The average value for each snow course is provided. The data are available from http://litdb.fmi.fi/eraclim2.php in Matlab and csv text files. Measurements from 1935 to 2014 are available.

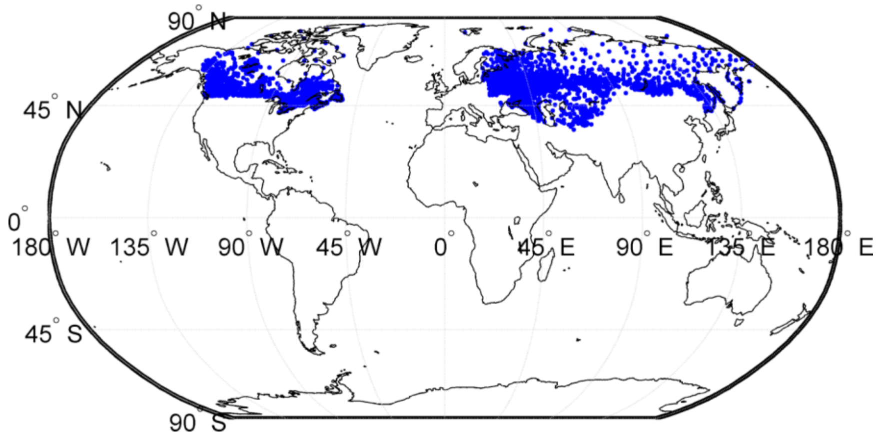

Figure 23 Coverage of the ERA-CLIM-2 in situ SWE data set.

The exact measurement protocol varies between Finland, Russia and Canada. The length of the snow course varies, as does the distance between manual SWE measurements. In closed forests in Russia, the length of the snow survey is 500 m with snow depth measured at 10 m intervals, and snow density every 100 m. In open canopy forested regions the length of the snow survey is 1 km, while in steppes the length of the snow survey is 2 km. For both of these land cover types, snow depth is measured every 20 m, and snow density at 200 m intervals (sometimes every 100 m). Measured snow depth and snow density were averaged along the path, and water equivalent calculated as SWE = 10dh (mm), where d = density (g/cm3) and h = depth (cm). In Finland, the procedure is similar to Russia. A snow course is from 2 to 4 km long and each course is measured once or twice a month. Snow depth is measured every 100 m and density every 500 m. The courses in Canada are shorter, typically 5-40 samples of snow depth and density.

The data were manually recorded in log books and manually digitized. Duplicates, units, coordinates and other obvious errors have been checked when the data set was compiled.

2.4.7 Satellite products

GlobSnow Snow extent: FMI produces a global (excluding glaciers, Greenland, Antarctica and snow on ice) daily snow cover extent fractional product (Fig. 24) from ESA ERS-2 ATSR-2 and Envisat AATSR data. It is available from 1995 onwards in http://www.globsnow.info/index.php?page=SE. The baseline spatial resolution is 1 km. From 2000 onwards the resolution for complex terrain is 250 m to 500 m.

GlobSnow Snow water equivalent: FMI produces the GlobSnow snow water equivalent product version 2.0 for Northern Hemisphere (35N-85N, excluding glaciers and Greenland) from SMMR, SSM/I, and SSMIS sensors combined with ground-based weather station data from 1979 until present (Fig. 25). The accuracy of the SWE estimate is 30-35 mm, if SWE is less than 150 mm. The production system utilizes the SWE retrieval methodology of Pulliainen (2006) combined with a snow melt detection algorithm of Takala et al. (2009). The data resolution is 25 km x 25 km and daily, weekly and monthly products are available. The data format is NetCDF and HDF4. Data files include SWE estimates and accuracy estimates for each pixel. Daily, weekly and monthly products are available from http://www.globsnow.info/index.php?page=SWE.

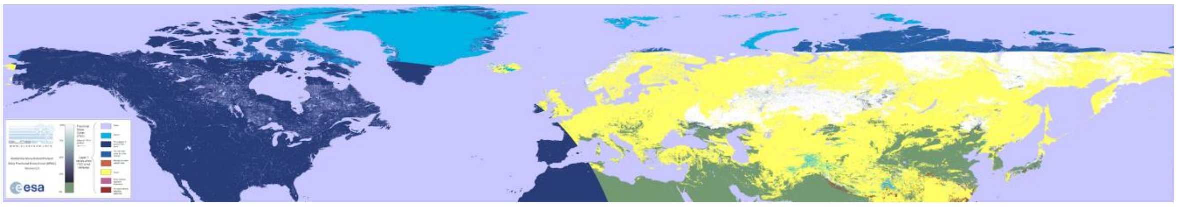

Figure 24. Fractional snow extent for 13 March 2018.

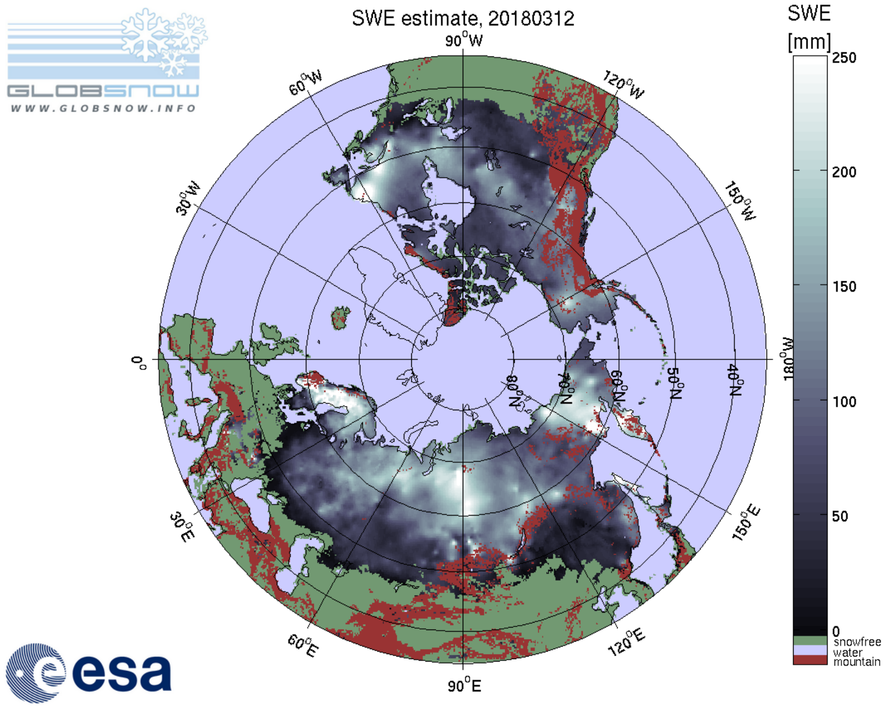

Figure 25. Northern Hemisphere SWE for 13 March 2018.

ERA-CLIM2 Northern Hemisphere snow water equivalent: FMI produced a new version of the GlobSnow long term global SWE record within the EU ERA-CLIM-2 project for years 1979-2016. The spatial representation of the snow extent during the winter and spring snow seasons was improved. The original GlobSnow v2.0 SWE product was combined with a JAXA-produced daily optical snow cover extent product, improving the consistency of the long term record, and capturing the snowline more reliably. The product is available at http://www.globsnow.info/swe/archive_v2.1_Eraclim/.

AMSR-E/Aqua Daily L3 Global Snow Water Equivalent EASE-Grids, Version 2: NASA provides level 3 snow water equivalent data sets from Aqua/AMSR-E. The data are global with

25 km x 25 km resolution in EASE grid. Daily, 5 day and monthly data are available from Feb 2002 to Oct 2011. Quality-flagged data are available in HDF-EOS format from http://nsidc.org/data/AE_DySno/versions/2. Data user guide is available in http://nsidc.org/data/AE_DySno/versions/2. Files contain core metadata, product-specific attributes, and 721 rows x 721 columns pixel data fields in 1-byte unsigned integer format. Actual SWE values are scaled down by a factor of 2 for storing in the HDF-EOS file.

JASMES snow depth: JAXA produces a global daily snow depth product from GCOM-W1/AMSR2, Aqua/AMSR-E and ADEOS-II/AMSR data. Data are available through https://gcom-w1.jaxa.jp/auth.html. The resolution of the product is 30 km. The accuracy of the product is +/- 20 cm.

MODIS/Aqua Snow Cover Daily L3 Global 500m Grid, Version 6: NASA produces the daily, gridded snow cover and albedo derived from radiance data from Aqua/MODIS. The product is available from https://nsidc.org/data/mod10a1. Snow cover is identified using the Normalized Difference Snow Index (NDSI) and a series of screens designed to alleviate errors and flag uncertain snow cover detections. Spatial resolution is 500 m x 500 m.

2.5. SMHI

2.5.1 Arctic Hydrological Cycle Observing System (Arctic-HYCOS)

The Arctic-HYCOS (www.whycos.org/whycos/projects/under-implementation/arctic-hycos) is an observation system under implementation by the National hydrological services (NHS) in Canada, Denmark, Finland, Iceland, Norway, Russian Federation, Sweden, and United States of America, in collaboration with The Global Runoff Data Centre (GRDC, www.bafg.de/GRDC) and the World Meteorological Organization (WMO, www.wmo.org). Arctic-HYCOS is intended to serve as a component of the World Hydrological Cycle Observing System network (WHYCOS, www.whycos.org), providing **river discharge** data from a network of hydrological stations operated by the NHS in the pan-arctic drainage basin of the Arctic Ocean and northern seas.

This assessment is focused on spatial and temporal coverage in relation to the objectives for the observation system, defined by the Arctic-HYCOS project steering committee:

- To provide data suitable for evaluating freshwater flux to the Arctic Ocean and northern seas, and
- To provide data suitable to study changes in Arctic hydrological regimes relative to climate change.

These objectives were transformed into corresponding requirements including specifications for the spatial and temporal coverage; see further details in section 3.1.

The Arctic-HYCOS dataset was further enhanced with regard to temporal and spatial coverage by combination of data from GRDC and NHS repositories, and with regard to station metadata; see INTAROS deliverable D2.8.

Arctic-HYCOS station network

The Arctic-HYCOS network is composed of stations from the regular observation networks, selected by the NHS for each country as suitable to fulfill the objective of the observation system. The stations are divided into two sub-networks:

- **Hydrological regime stations** covering the entire land mass draining into the Arctic Ocean and northern seas. There is no limitation to the size of land area drained; long term gauges are prefered but not necessary; ideally a wide geographical distribution is expected.

- **Flow-to-ocean stations** are the most downstream monitoring stations that would be used to estimate total river flow to the Arctic Ocean and northern seas. This is a subset of the Hydrological regime stations. Stations are limited to those greater than 5000 km^2.

The current network includes 427 stations of which 71 are classified as part of the flow-to-ocean network. This list was provided for the INTAROS assessment by the Arctic-HYCOS Steering committee (latest update 2018-05-12). The station list is still under revision by the Arctic-HYCOS project and is expected to be finalized and published at the GRDC website during 2018.

Arctic-HYCOS station metadata

The Arctic-HYCOS station metadata contains the essential information about the station location (latitude, longitude), the area of the upstream drainage basin (km2), the station identifiers in the HYCOS, GRDC, and NHS data repositories, as well as station and river name, temporal coverage, sub-network (flow-to-ocean), and links to web-services providing realtime and historical data from the NHS if available. A spatial polygon defining the upstream drainage area, and a simplified quality flag will be implemented in the final version. The metadata definition was adopted from the WIGOS metadata standard for meteorological data (WMO, 2017), the GRDC metadata, and adapted to a minimum list of common attributes available from the different NHS.

River discharge is defined as the average flux of water (m^3/s) through a cross-section of the river at the location of the river. However, this flux represents the aggregated hydrological response of the upstream drainage area of the river cross-section. A spatial polygon for the drainage basin of each station will be implemented as a required metadata to improve the interpretability and usability of the data. The current version of the Arctic-HYCOS metadata does not provide these polygons, and were left out from the current assessment. GRDC provides on request drainage basin polygons derived from the HydroSHEDS elevation data available below 60°N. Assessment of these data versus nationally defined drainage basins, and basins derived from the high resolution Arctic-DEM data will be performed at a later stage.

It should be noted that no information related to instrumentation, validation and quality assurance procedures, originally measured data (water levels), transformation algorithms (so-called rating curves), scientific support, and technical readiness level is provided by neither the Arctic-HYCOS or the GRDC metadata. To some extent, such information was collected from the web services of the NHS.

Additional data used for the assessment and enhancement of the Arctic-HYCOS data

Additional information for the assessment and enhancement was taken from the global GRDC station list (http://www.bafg.de/GRDC/EN/04_spcldtbss/41_ARDB/ArcticHYCOSData.html), information compiled from the R-ArcticNet data (www.r-arcticnet.sr.unh.edu), as well as a network of sub-basin drainage basins delineated for the Arctic-HYPE model (hypeweb.smhi.se/arctichype), using a high resolution flow accumulation and elevation data (90x90m) from the GWD-LR dataset (Yamazaki et al, 2013).

Characterization of the geographical and landscape representation was further assessed by analysing overlay of the drainage basins with the land cover data (ESA CCI land cover), soil type (Harmonized World Soil Database) as prepared for the Arctic-HYPE model. A method for deriving the effective drainage area using the high resolution ArcticDEM (www.pgc.umn.edu/data/arcticdem/) elevation data was developed as part of the enhancement of the arctic-HYCOS station metadata.

Arctic-HYCOS river discharge data

Arctic-HYCOS river discharge time-series data with monthly and daily value were collected from several sources:

1) The GRDC Arctic-HYCOS database, which is available for free download as a compressed zip-archive. This archive currently contains data for 351 of the 427 stations latest updated 2017-12-31.
2) The global GRDC data collection, including additional stations recently provided by the Arctic-HYCOS partners. Data available after request through a web-form.
3) Data available from NHS services in Canada, USA, Finland through open web services.
4) Data available from Iceland and Norway, available through email request.

The current Arctic-HYCOS metadata table includes GRDC identifier for 353 of 427 stations. Additionally 40 stations (in total 393) could be linked to the GRDC repositories using national stations identifiers and/or station location and upstream area. However, time-series data could only be found for 351 of these stations in the GRDC databases (obtained 2017-11-16). Time-series data for additionally 65 stations, including 7 flow-to-ocean stations, were obtained directly from the national hydrological services in Canada, USA, Finland, Iceland and Norway. Discharge data from 11 of the Arctic-HYCOS stations were not included, since these were added to the station list after the data collection for this assessment.

Temporal coverage

The temporal coverage of the Arctic-HYCOS data is well above the required 30 year period for most of the stations. The longest time series from each country extends more than 100 years. However, it should be noted that the timeliness of updated historical data sets vary substantially between the countries, for some at best 2 years, and for others within a year. The access to real-time observations with timeliness of 1 day is only available from the USA, Canada, Finland, and Norway.

Spatial and flow-to-ocean coverage

The spatial coverage and the flow-to-ocean coverage of the Arctic-HYCOS stations were assessed using the Arctic-HYPE model (Andersson et al, 2015; Gelfan et al, 2017; http://hypeweb.smhi.se/arctichype). The total drainage basin of the PADB was delineated and divided into sub-basins using the GWD-LR (Yamazaki et al, 2013) flow direction and flow accumulation data. The spatial coverage of the Arctic-HYCOS network and sub-networks was estimated by comparing the drainage basin of the stations with the drainage basin of the corresponding outlet sub-basins in the model. The total flow-to ocean was estimated using the Arctic-HYPE model corrected by the mean relative volume error (-17%) compared to the observations at the HYCOS flow-to-ocean stations. The flow-to-ocean coverage of the HYCOS stations was then calculated as the fraction of the flow-to-ocean estimated by the model.

The assessment of Arctic-HYCOS river discharge observations show that the spatial coverage of the flow-to-ocean network is about 52% of the Pan-Arctic Drainage basin (PADB) of the Arctic Ocean and northern seas as defined by the Arctic-HYCOS project. The spatial coverage is between 55-60% for the coastal areas in North America and the Russian Federation, whereas the coverage is only 15% in Iceland, Scandinavia and Svalbard. Greenland is practically not covered at all. On the other hand, the freshwater flux to the ocean from Greenland involves also the flux of ice mass, which is not the intention of the Arctic-HYCOS network. The Greenland freshwater flux to the ocean is also estimated by GEUS in one of the enhanced observation systems (see D2.8). By extending the flow-to-ocean network to additional stations most downstream to the ocean with basin area >5000 km2, the spatial coverage can be improved up to 69 % in Russia and 58% in total.

The representation of the total river discharge to the ocean (excluding Greenland) by the flow-to-ocean network is about 55%, which can be further increased to 61% by including the extended flow-to-ocean stations. The distribution between the Eurasian and North American rivers is however somewhat different. According to this assessment the river flow in the Russian rivers is represented to 65% (75%) by the flow-to-ocean observations and the flow in the North American rivers only by 54 % (56%), with numbers for the extended flow-to-ocean network in brackets. However, these figures are relying on the estimates by the Arctic-HYPE model, which even if the average bias has been accounted for, is known to overestimate flow in the Hudson Bay area in particular.

2.6. USFD

2.6.1 Eddy covariance towers

To evaluate how representative our eddy covariance (EC) towers are of the larger areas around them we used footprint analysis to compare what the eddy covariance towers are sampling in the 1 km^2 grid around them (Reuss-Schmidt et al., in preparation). This analysis resulted in a time series of the changes in the ecosystem properties sampled, as the footprint changes with wind speed and direction. This change does not result from the temporal variability in the explanatory variable, but from the variability in the spatial sampling properties of the EC measurement as the area sampled by the tower changes over time (Fig.26).

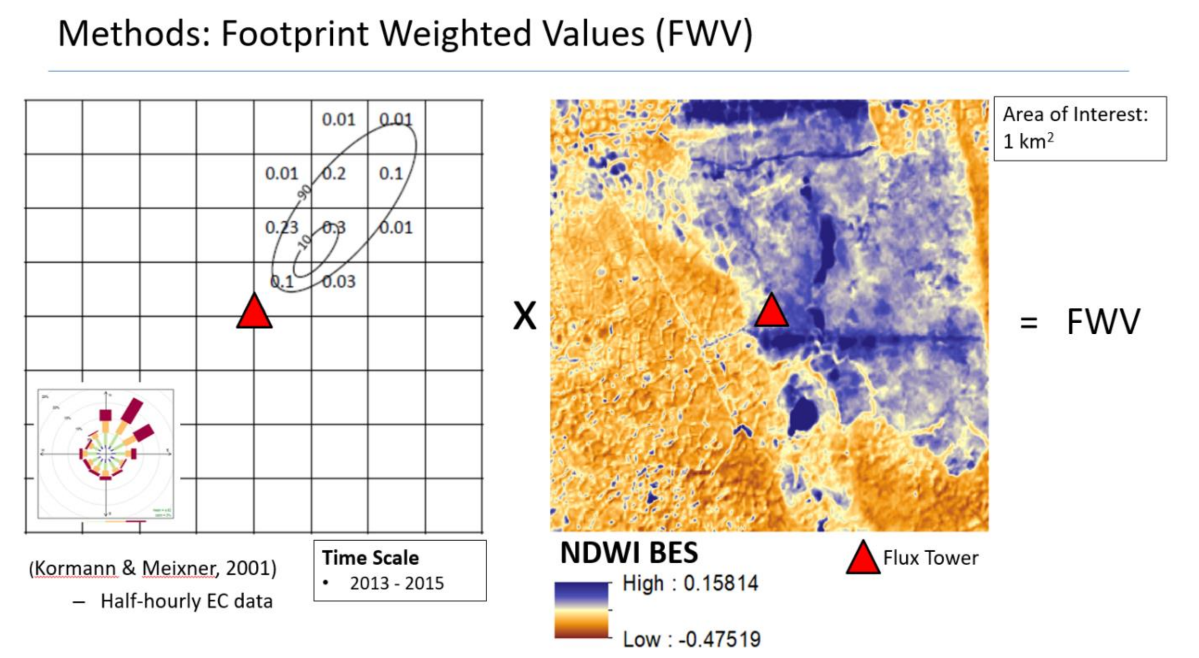

Figure 26. For each half-hour the Kormann and Meixner (2001) calculates a probability distribution of where the fluxes are coming from. This distribution is represented by the 10% and 90% isolines, which indicated that 10% and 90% and of the fluxes are occurring within the smaller and larger oval, with a confidence level of 95 %.

This distribution is used to assign a flux contribution to each cell of a raster grid. This raster is then multiplied by the raster of the relevant spatial indices (normalized differential water index [NDWI] is used for this example). The values in the resulting raster are then summed to produce a footprint-weighted value ($\hat{I}$). The $\hat{I}$ is the mean value of the spatial index corresponding to each methane (CH_4) flux observation.

The footprint-weighted spatial indices $\hat{I}$ were compared with their mean over the wider domain to assess how representative the area sampled by the tower was. As a summary statistic, we calculated the sensor location bias developed by Schmid and Lloyd (1999) and Chen et al. (2011).

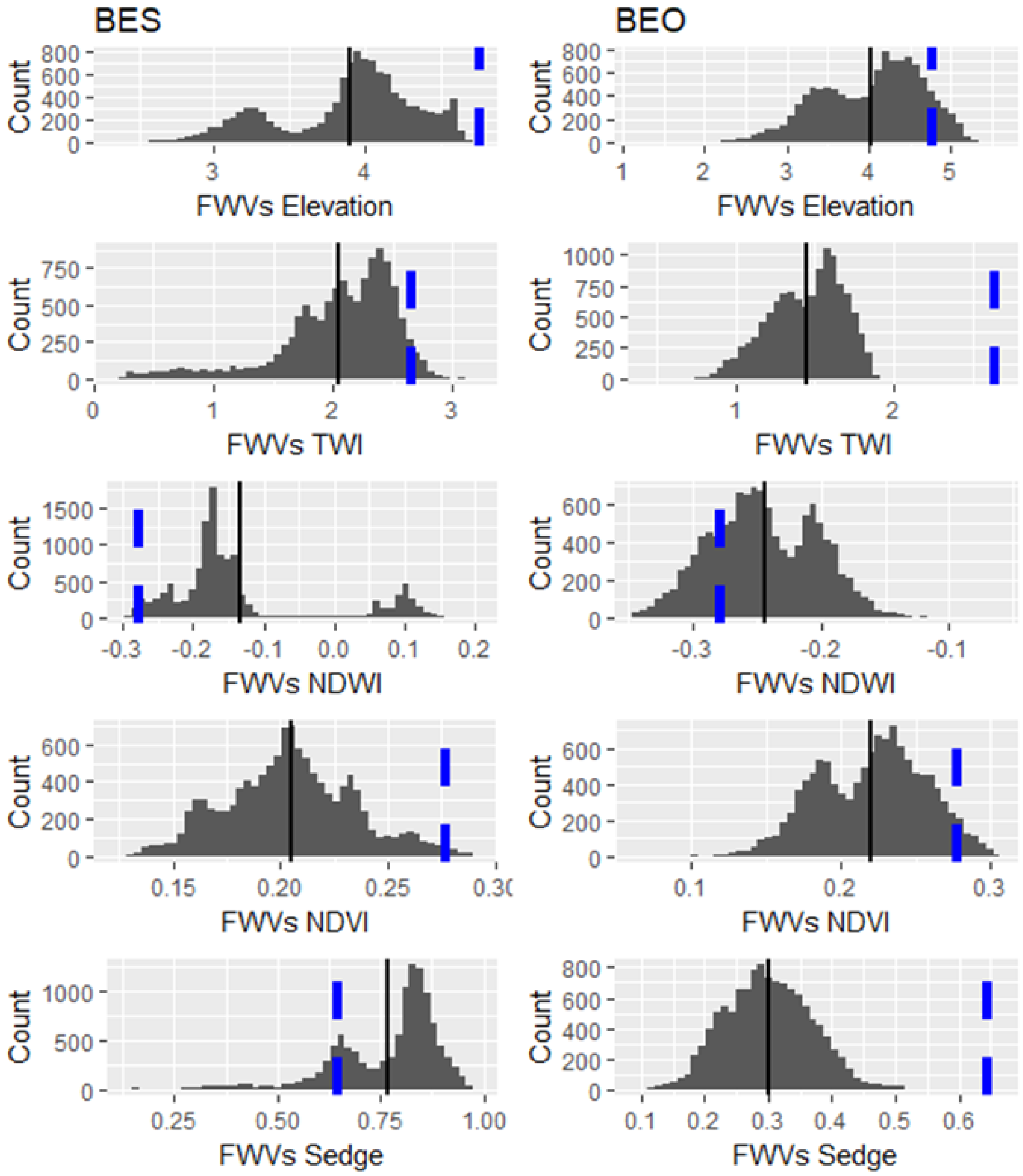

Figure 27. Each count represents one footprint-weighted spatial index, i.e. the average value of the spatial index for one half-hourly flux observation. The mean of the footprint-weighted spatial index is shown by the solid thin black line and the mean for the unweighted local domain is shown by the dashed thick blue line. The histograms have a bin size of 50 and include all data suitable for footprint modelling from 2013-2015.

The footprint modelling showed that there was substantial variability in the footprint-weighted spatial indices over time (Fig. 27). The means of the footprint-weighted spatial indices deviated substantially from the means for the wider 600 x 600 m domain; the magnitude of sigma, δ, varied among sites and the indices considered, ranging from 18 - 51% (Fig. 27). The wettest site (BES) has the higher sedge cover.

The modelling indicates that spatial heterogeneity explained observed variability in the flux measurements. This was shown by all the methods for detecting this effect. Firstly, when the temporal variation in the other driving variables was accounted for, the footprint-weighted spatial indices explained 10-12% of the remaining variability. Secondly, even in the absence of any other variables, the footprint-weighted spatial indices could explain 35% of the variability, although some of this was confounded with temporal variability.

Overall, we found that the footprint variability has a significant influence on the observed methane fluxes, contributing to approximately 10 - 30% of the unexplained variability in CH_4 fluxes. Multiple spatial indices were used to define spatial heterogeneity, and their importance varied depending on site and season, but the normalized NDWI had the most consistent explanatory power. A spatial bias (i.e. difference in the spatial indices between the area sampled by the tower and the wider domain) of 18% suggested the need to consider the footprint when upscaling the fluxes to a wider region around the towers in these tundra ecosystems. This analysis highlights the challenges of using the available towers to infer the larger scale carbon balance from these highly heterogeneous polygonized tundra ecosystems, and suggests the need to evaluate the representativeness of the current towers across the pan-Arctic regions.

2.7. MPG

Within the context of INTAROS WP2, MPG aims at assessing the representativeness of the existing atmospheric observational infrastructure to monitor greenhouse gas fluxes in the Arctic. Two separate observational platforms are considered, i.e. the network of eddy-covariance (EC) flux sites in high northern latitudes, and the tall tower observations of atmospheric greenhouse gas mixing ratios that can be used in atmospheric inverse modeling studies to constrain regional to pan-Arctic scale greenhouse gas budgets. In both cases, we are not using the actual observational datasets (e.g. flux time series from the EC systems) for our analysis, but only metadata on e.g. site location and characteristics, temporal data coverage, and gas species monitored.

2.7.1. Eddy covariance network assessment

The analysis of EC network representativeness in the Arctic is based on the following steps:

1. Generate an inventory of existing EC greenhouse gas monitoring sites;
2. Compute current representativeness, separated by flux type (e.g. for CO_2 and CH_4 fluxes);
3. Combine the spatial representativeness analysis with temporal coverage for spatiotemporal coverage maps;
4. Identify realistic locations for additional sites, aiming at generating the biggest impact on network performance for pre-defined resources.

The links between these four elements are indicated in Figure 28. The analysis of the EC network is based on an inventory of existing sites within the Arctic domain, including an overview on historic data coverage (also covering discontinued sites). As a starting point, we gathered all available metadata from various database clusters within the EC community, including e.g. FLUXNET, the European Fluxes Cluster Database, AmeriFlux, or ICOS. These sources provided on overview on more than 100 individual measurement locations within the domain > 60° N. However, a closer inspection made it clear that the reported metadata were often incomplete, outdated, or in some cases even contradictory between overlapping sources. Moreover, detailed data coverage information was often absent, and several recently established sites were not presented at all.

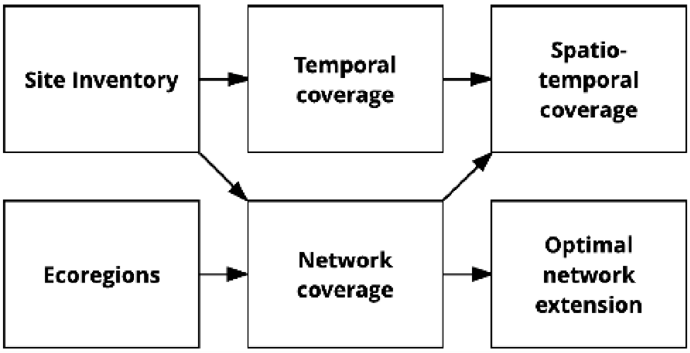

Figure 28. Conceptual overview on the network representativeness evaluation study.

To refine our overview on existing EC flux databases, we designed an online survey tool (http://capalonga.bgc-jena.mpg.de/mpall/), and distributed it among site PIs to obtain correct and up-to-date metadata information. A central part of this survey targeted the monthly data coverage across data years, which also allows differentiating network coverage analysis between, e.g., summertime and wintertime conditions. At the time of reporting, the survey is ongoing, and we are still collecting input from site PIs (> 60 answers so far). The total number of sites has been extended to 129 now, with 36 listed as inactive. Figure 29 indicates a first survey on long-term trends and seasonal variability in temporal coverage for a core subset of sites where detailed information is available.

A clear seasonal pattern emerges already from this first visualization, with data coverage at many sites discriminating against wintertime measurements. A survey plot on the long-term temporal development of EC data coverage (Figure 30) demonstrates that the number of sites has increased over a period of 25 years starting in the early 1990s. The total number of sites has risen from less than 4 at the beginning of the period to close to 90 since around 2010, while the average activity period increased from 2.5 to 4.3 years (longest continuous record: Barrow (CMDL), 24 years). The majority of sites (60%) are situated in Europe and Alaska. Only 46% of the sites in the region > 60° N are indeed 'Arctic' sites, i.e. located North of the Arctic circle, while about 50% represent a forested ecosystem. Only 53 sites also capture CH_4 fluxes (12 listed as inactive), and those typically feature shorter time series, compared to CO_2 observations. The data covered currently by our Arctic site survey splits into the following categories regarding data availability:

1. Open-access: 18%
2. Available on request through the PI: 44%
3. Planned to be made available in future: 36%
4. Data not available: 2%

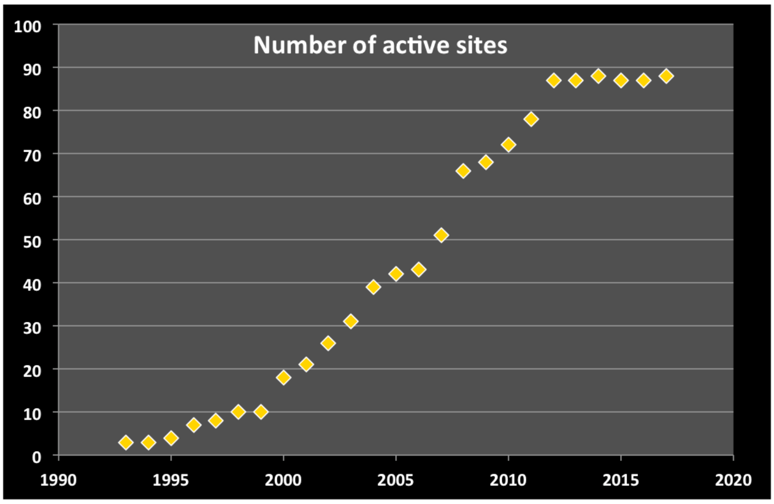

Figure 30. Development of the total number of active sites in the period 1993 - 2018.

To facilitate the consideration of variability in climate and ecosystem characteristics in the network representativeness study, we organized the Arctic domain into distinctive so-called ecoregions. The definition of these ecoregions is based on the combination of a number of 18 prime ecosystem variables (10 bioclimatic, 5 edaphic/topographic, 3 permafrost-related), including, for example, monthly mean temperature, elevation, and length of the growing season. The metrics that are used to differentiate between ecoregions types are based on multivariate spatiotemporal clustering. The total number of ecoregions to be defined by the algorithm can be prescribed by the user.

Each network representative study needs to be initialized by selecting a subset of sites from the total list of EC towers. Site subsetting within this study by MPG considers, e.g., flux species (e.g. CO_2, CH_4), coverage within certain periods (e.g. 5-year bins), and summertime vs. wintertime networks. The overall representativeness of the entire network can then be estimated through quantifying the relatedness of prevailing conditions at the EC tower locations with either ecoregions or individual cells within the (gridded) Arctic study domain. As a measure of relatedness, we use the Euclidean distance within the list of prime ecosystem variables. The representativeness of multiple sites can be combined into an overall representativeness of the Arctic eddy covariance network compared to the Arctic ecosystems (see e.g. Figure 31). The maps shown in Figure 31 (left) clearly indicate that most areas of the European Arctic and Alaska are well covered by the existing network of EC towers. Large parts of Canada and Russia are sparsely covered, leaving many areas with poor data availability. Multiplying by additional environmental parameters, such as, e.g., soil organic carbon content (Figure 31, right) can further change the obtained patterns, allowing investments to be directed into enhanced observational infrastructure to locations that are both poorly represented by the existing sites and vulnerable hotspots in the context of future climate change. From representativeness maps such as those in Figure 31, both pan-Arctic and regional minima in network coverage can be identified as the least represented single locations (Figure 32).

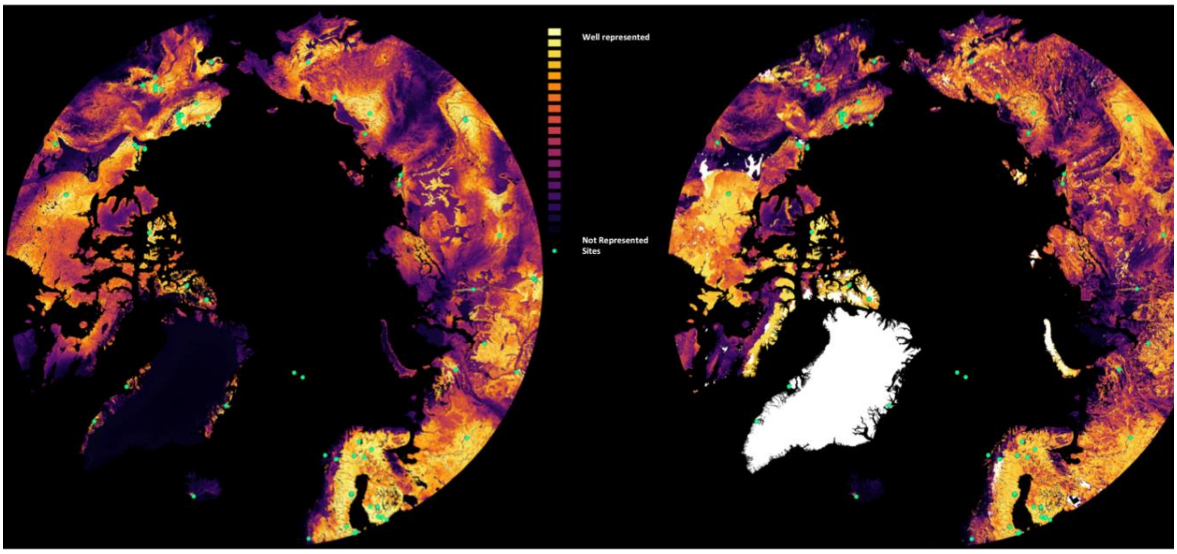

Figure 31: Example results on the representativeness of the Arctic EC network, with lighter colors (yellow) indicating well-represented areas, while darker colors (purple) show under-represented regions. Left panel: basic representativeness for the chosen subset of sites, where green dots mark the location of EC sites used for the analyses. Right panel: representativeness multiplied by soil organic carbon as a measure for potential carbon release under future climate change, where green dots mark the least represented area per country.

The subsequent steps in this study will focus on refining the subsetting of sites, in order to analyze network representativeness based on additional qualifiers as outlined above. However, a final version of our results can only be computed once we have finalized the EC site survey, thus have access to the full set of metadata information on the Arctic EC network. Moreover, we are underway in integrating an alternative method for assessing network representativeness based on the K-nearest neighbours method. This new approach will allow input variables to be weighted according to their impact on the flux under investigation. Furthermore, the new output metrics will create clear cutoffs between interpolated and extrapolated cells. A first preliminary example result for this second evaluation metric is shown in the following Figure 33.

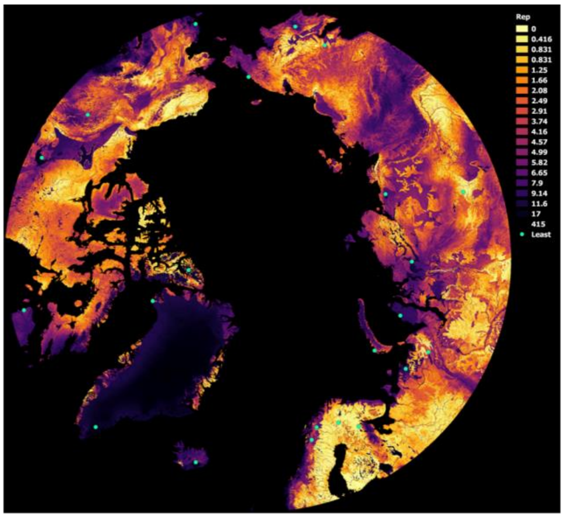

Figure 32: Example for the selection of sites representing regional minima in computed network coverage, thus potential locations for network extensions.

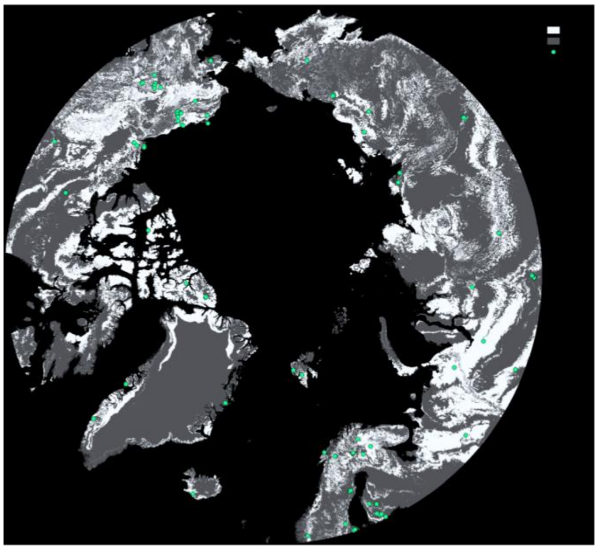

Figure 33: First results based on a K-nearest neighbour approach using environmental controls that have been scaled according to their relevance for carbon cycle processes. The algorithm separates the model domain into 'interpolated' (white) domains that are well represented by the currently available observations (green dots: site locations), and 'extrapolated' (grey) regions where conditions significantly deviate from those covered by the network of observation sites.

2.7.2. Tall tower network for atmospheric greenhouse gases

To evaluate the capabilities of the pan-Arctic atmospheric tower network, an Observing System Simulation Experiment (OSSE) is planned. In an OSSE setup, a predefined environment is created, i.e. we will set up a modeling framework that combines spatiotemporal variability in surface emissions with atmospheric transport pattern to simulate synthetic observations of atmospheric mixing ratios. These observations are subsequently modified (disturbed) to represent realistic levels in, e.g., observational and transport uncertainties, then supplied to an inverse atmospheric model through which source concentrations can be inferred. These in turn can be compared to the original predefined environment. The major advantage with this set-up is the option to simulate certain emission scenarios, e.g., enhanced outgassing from degrading permafrost areas along the ocean shelves, and test whether or not such signals could be captured by the existing observational infrastructure. At the same time, the effect of adding new sites on the posterior uncertainties of an inversion output can be directly quantified.

Our main research question will investigate potential gaps in the Arctic monitoring network for atmospheric CO_2 and CH_4 mixing ratios. Based on this assessment, we will analyze through the synthetic experiments outlined above what types of sources/sinks for Arctic greenhouse gases can be constrained with what level of accuracy through atmospheric inverse methods.

At time of reporting, we have generated an overview on the currently available observational infrastructure for Arctic greenhouse gas mixing ratio monitoring in the atmosphere, and supplied this information through INTAROS WP2 questionnaires A and B. An overview on the tower network is shown in Figure 34 below. The atmospheric transport simulations that are required to link each of these towers to its source region, and the temporal variability therein, are being processed at the time of writing, so that MPG expects to start first pan-Arctic simulations in the context of an OSSE in April 2018.

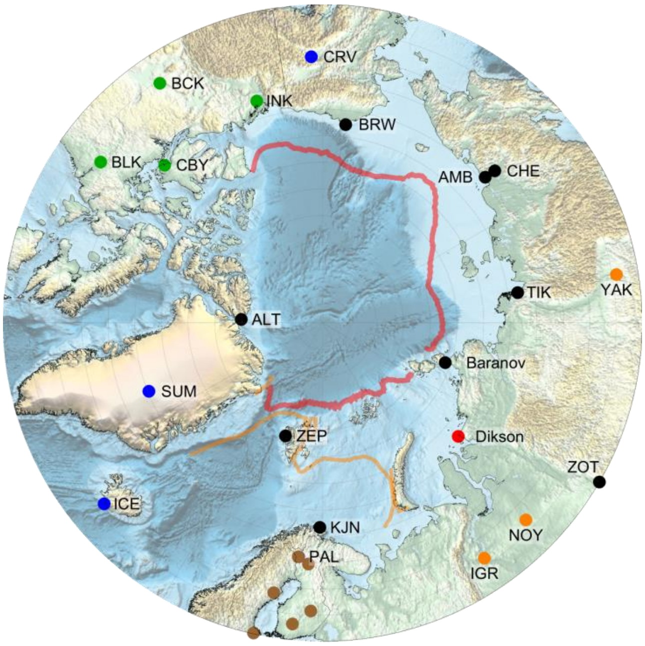

Figure 34: Overview on the currently active network of atmospheric tall towers to monitor greenhouse gas mixing ratios in the Arctic domain.

2.8. UPM

The data used by UPM researchers to develop the demonstrations of the iAOS for stakeholders to be undertaken under Work Package 6 all use source data from external (to INTAROS) existing observing systems and already available data collections, though UPM has contributed to collect, process and document some of these data. These data include:

- surface mass balance (SMB), both point and glacier-wide, as well as density point data, from the Fluctuations of Glaciers (FoG) database hosted by the World Glacier Monitoring System (WGMS),
- glacier ice-thickness data from the Glacier Thickness Database (GlaThiDa), also hosted by the WGMS, and
- the data on glacier outlines in the Randolph Glacier Inventory (RGI) hosted by the National Snow and Ice Data Center (NSIDC).

Each of these databases has undergone a different data preparation, most often done externally to INTAROS, and most often involving diverse research teams. This implies that, even for data from a given database, the data collection and early-stage procedures of data preparation can present some differences. Obviously, at the time of uploading these data to the corresponding databases they have been unified to a common format. As mentioned, UPM researchers have contributed to several of these open-access databases with UPM's own collected data, and consequently been involved in the associated data preparation. We describe below the essentials of the data in each of the above-listed databases and the main facts regarding the data preparation. In Section 2.17 of Deliverable 2.8 we describe the methods developed by UPM team to calculate, using all of these data, plus other satellite observing systems (such as Sentinel-1), the ice discharge to the ocean from Arctic tidewater glaciers, and to separate, for selected glaciers, the frontal ablation into its two main components, namely glacier calving and submarine melting at the glacier front.

All of the above-listed databases host data from around the globe, although we will focus our analysis on those in the Arctic region. Since some of these databases have data from hundreds and even thousands of glaciers, we do not include here a precise location map but, instead, a map with the polygons defining the various glacier regions, following the naming convention of Glacier Regions by the Global Terrestrial Network for Glaciers (GTN-G) (http://dx.doi.org/10.5904/gtng-glacreg-2017-07).

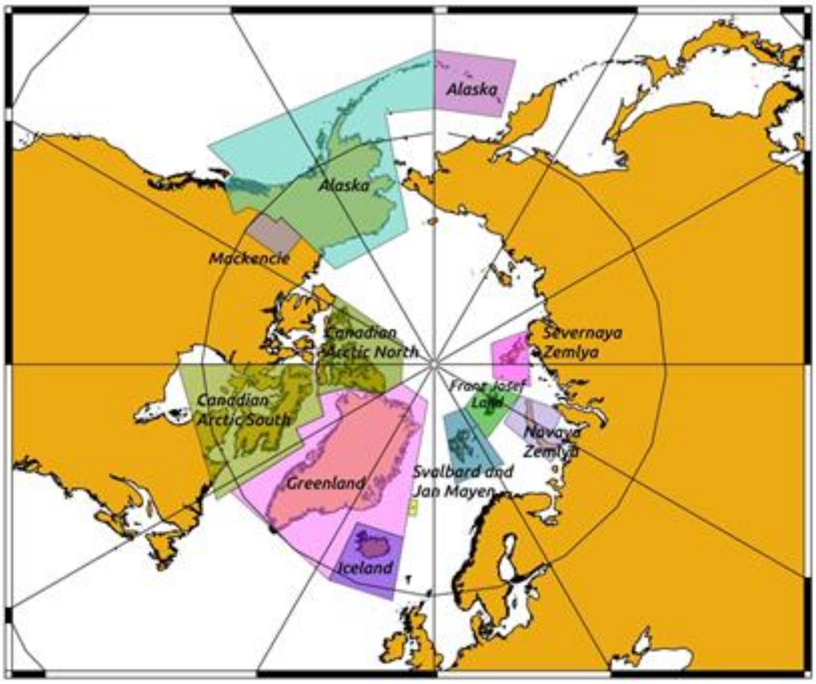

Figure 35. Location map of the the various glacier regions considered in this study, following the naming convention of Glacier Regions by the Global Terrestrial Network for Glaciers (GTN-G).

2.8.1. World Glacier Monitoring Service (WGMS)

It collects standardized observations on changes in mass, volume, area and length of glaciers with time (glacier fluctuations), as well as statistical information on the distribution of perennial surface ice in space (glacier inventories) (Zemp et al., 2009). The information was traditionally structured and made available through two main products:

- The Glacier Mass Balance Bulletin (GMBB) (ISSN 1997-9088 (print) and 1997-9096 (online)), published at two-year intervals and covering the period 1988-2011.

- The Fluctuations of Glaciers (FoG) series (ISSN 1997-910X (print) and 1997-9118 (online)), published at five-year intervals and covering the period 1959-2010.

Since 2015 they have been merged into the Global Glacier Change Bulletin (GGCB) series, published at two-year intervals (doi:10.5904/wgms-fog-2015-11 for 2015 volume). Online access to the main data is provided through the FoG browser http://wgms.ch/fogbrowser/

The particular variables/data collections that we analyze are:

- Point surface mass balance (winter, summer, annual).
- Point snow density (winter, summer, annual).
- Glacier-wide surface mass balance (winter, summer, annual).

Data preparation

The data collection is organized through a global cooperative network of National Correspondents and Principal Investigators. Usually SMB is calculated using the glaciological method (Cogley, 2011). Based on accumulation and ablation data collected at nets of stakes deployed on the glacier surface, the snow thickness data from snow probing and the density data measured at the snow pits, point SMBa (winter, summer, annual) are calculated. These point SMBs are then integrated over the glacier area to determine glacier-wide winter, summer and annual SMBs. The SMB is also calculated by elevation bands, and the elevation of the band with zero SMB is taken as equilibrium line altitude (ELA). The areas with net annual accumulation and ablation are calculated and the quotient of accumulation area total area defines the accumulation area ratio (AAR).

The WGMS database is structured into the following units (the main data for each one is listed; all of them –except General Info.– include additionally investigator and sponsoring agency, and survey date and method, when applicable, as well as accuracy estimates):

- General Information: glacier name and ID, location, type, form and orientation.
- State: year, maximum and minimum elevations, length.
- Front Variation: front variation data.
- Change: lower and upper boundaries, area, area change, thickness change and volume change for each altitude interval.
- Mass Balance Overview: time measurement system, begin and end of survey period, ELA, number of measurement sites on the accumulation and ablation areas, areas of the accumulation and ablation zones, AAR.
- Mass Balance: lower and upper boundary of altitude interval, altitude interval area, specific (per unit surface) winter, summer and annual balances for the whole glacier.
- Mass Balance Point: point ID, latitude, longitude and elevation, point winter, summer and annual balances, density.
- Special Event: event date, type (surge, calving, flood, ice avalanche, tectonic event) and description, and data source.

The full database is provided as a set of ASCII (.csv) files.

2.8.2. GlaThiDa database

It is an internationally collected, standardized dataset on glacier thickness from in situ and remotely sensed observations, based on data submissions, literature review and airborne data from NASA’s Operation IceBridge (Gärtner-Roer et al., 2014). GlaThiDa is maintained under the frameworks of the Global Terrestrial Network for Glaciers (GTN-G), jointly run by three operational bodies: the World Glacier Monitoring Service (WGMS), the US National Snow and Ice Data Center (NSIDC), and the Global Land Ice Measurements from Space (GLIMS) initiative.

It is a downloadable database (no access to individual data through data browser). The most recent version is V2.0, released on 04/07/ 2016, with DOI 10.5904/wgms-glathida-2016-07.

Data preparation

The data collection is organized through a global cooperative network of Principal Investigators. Most data are collected using ground-penetrating radar in the form of profiles, which have to be processed using standard techniques for reflection data processing (normal moveout correction, spatio-temporal filtering, migration, topographic correction, etc.).

GlaThiDa is structured into three data tables:

- T - Glacier Thickness Overview: containing information on the location and area of the glacier, estimates of mean and maximum thickness from interpolated observations including accuracies, the survey data, method and related information, as well as investigator and source of the data.
- TT - Glacier Thickness Data Derived From Map or DEM: includes ice thickness data (mean and/or max) averaged over surface elevation bands by given lower and upper boundaries from ice thickness maps or Digital Elevation Models (DEMs).
- TTT - Glacier Thickness Point Data: contains point data including a point ID, related coordinates, the elevation at the surveyed point, as well as the thickness value. This table TTT reflects the original observations.

All tables include the given GlaThiDa ID, political unit, glacier name and date of the survey The GlaThiDa ID serves as primary key and links information from corresponding surveys in all three tables. The full database is provided as a set of ASCII (.csv) files.

2.8.3. Randolph Glacier Inventory

It is a global inventory of glacier outlines. It is supplemental to the Global Land Ice Measurements from Space initiative (GLIMS) (Pfeffer et al., 2014). Future updates are planned to the RGI and the GLIMS Glacier Database in parallel during a transition period. As all these data are incorporated into the GLIMS Glacier Database and as download tools are developed to obtain GLIMS data in the RGI data format, the RGI will evolve into a downloadable subset of GLIMS, offering complete one-time coverage, version control, and a standard set of attributes. The most recent version is V6.0, released on 28/07/2017 (DOI 10.7265/N5-RGI-60).

Data preparation

The data collection is organized through a global cooperative network of Principal Investigators. In the preparation of the RGI, glacier outlines that were separated from their neighbors when received were accepted without change, subject only to the quality control described below. Glacier outlines originally obtained as glacier complexes (collections of contiguous glaciers that meet at glacier divides) were separated into individual glaciers using a semi-automated algorithm. The quality of the output primarily depends on the quality of the DEM available. Additional manual checks were carried out in Alaska, Arctic Canada South and Greenland.

Quality checks were conducted on all glacier polygons. These include geometry, topology and attribute-field checks.

The RGI is provided as shapefiles containing the outlines of glaciers in geographic coordinates (longitude and latitude, in degrees) which are referenced to the WGS84 datum. Data are organized by first-order region. For each region there is one shapefile (.SHP with accompanying .DBF, .PRJ and .SHX files) containing all glaciers and one ancillary .CSV file containing all hypsometric data. The attribute (.DBF) and hypsometric files contain one record per glacier.

2.9. U Exeter

2.9.1. Snow depth at eddy covariance towers

The depth and duration of snow cover on the Arctic tundra has complex effects on the soil physical environment, including soil temperature, moisture, and the duration of the period when soil remains unfrozen. Snow cover during spring/early summer in the Arctic has been declining by almost 20% per decade in recent years, a much higher rate than all models previously estimated (Derksen and Brown, 2012). The last decades witnessed an earlier spring snow-free date, later snow-cover onset, and decrease in snow-cover duration throughout the Arctic (Derksen and Brown, 2012). As a consequence, the length of the growing season has increased by 1.1 – 4.9 days per decade since 1951 (Menzel et al, 2006). On the other hand, winter warming (Bekryaev et al., 2010), and the increase in atmospheric moisture from increased evapotraspiration are increasing winter precipitation (Bintanja & Selten, 2015), and winter snow thickness across the Arctic (Hay & McCabe, 2010). A thicker snow layer increases soil insulation and as a result soil temperature and soil respiration rates leading to permafrost loss (Park et al., 2015).

Defining the impact of snow dynamics on Arctic CO_2 and CH_4 fluxes is very challenging because of the paucity of continuous surface observations. The cloud-prone nature of Arctic regions makes high resolution monitoring of snow cover changes and vegetation development with satellites extremely difficult (Stow et al., 2004). For example, snow and clouds can be easily confounded, decreasing the accuracy of a variety of available snow products (e.g. from Visible Infrared Imaging Radiometer Suite (VIIRS), and the Moderate Resolution Imaging Spectroradiometer (MODIS), Justice et al., 2013). On the other hand, snow cover estimates from microwave products such as Globsnow (http://www.globsnow.info/index.php?page=Snow_Extent) are less subject to biases due to the cloud cover but are only available at a spatial resolution (e.g. 1 km) larger than the footprint of the eddy covariance towers (100-200 m). It is also difficult to assess the snow depth from remote sensing, making ground observation particularly critical (Park et al., 2014). The few snow depth products available do not have data coverage in Alaska (e.g. Snow Data Assimilation System (SNODAS) Data Products at NSIDC, http://nsidc.org/data/docs/noaa/g02158_snodas_snow_cover_model/index.html), or have a very coarse spatial resolution (e.g. 32 km, http://www.esrl.noaa.gov/psd/data/gridded/data.narr.monolevel.html). Snow depth will be measured in all sites using snow sensors (model SR50A-L, Campbell Scientific, Logan, Utah, USA).

To address this shortcoming we evaluated the ability of snow depth sensors to capture snow depth, and the variability of snow depth across the same gridcell of the abovementioned coarse resolution remote sensing products. The snow depth was measured in the footprint of the eddy covariance towers using a Campbell Scientific model SR50A-L snow senor (Campbell Scientific, Logan, Utah, USA). The spatial variability of the snow depth in sites only hundreds of metres apart (e.x BEO, BES, and CMDL, Fig. 36-37), highlights the need for high spatial resolution to be able to capture the complexity of these ecosystems. An assessment of the availability of these measurements across the Arctic showed that site-level snow depth is not available from any of the Fluxnet or Ameriflux sites.

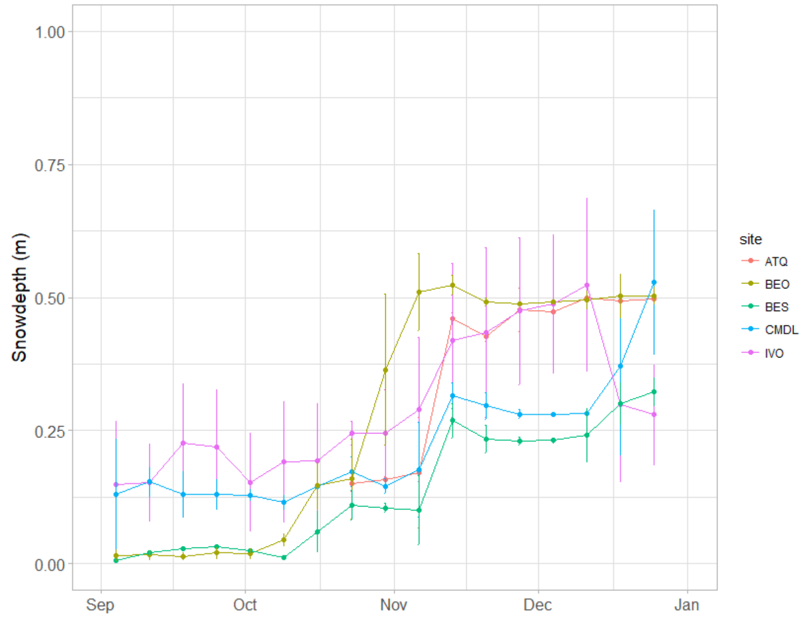

Figure 37. Snow depth measured in the footprint of the eddy covariance towers in Alaska in 2016, as in Fig. 36, but superimposed for comparison purposes.

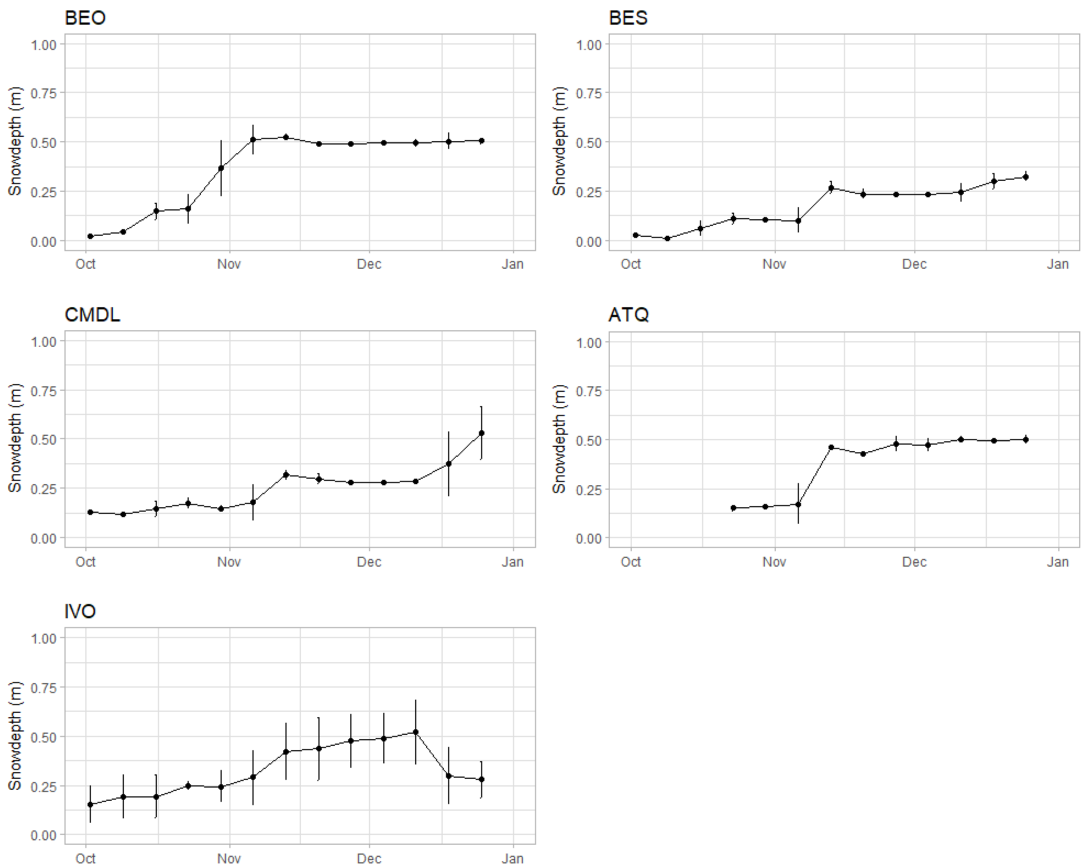

Figure 36. Snow depth measured in the footprint of the eddy covariance towers in Alaska in 2016.

2.10. U Helsinki

2.10.1. The Pan-Eurasian Experiment (PEEX)

PEEX (https://www.atm.helsinki.fi/peex), initiated in 2012, is an international, multi-disciplinary, multiscale program focused on solving interlinked global challenges influencing societies in the Northern Eurasian region and in China. As a part of the program, PEEX aims to establish an in situ observation network, which would cover environments from the Arctic coastal regions, tundra to boreal forests, from pristine to urban megacities. The PEEX network will be based on two components: (i) existing station activities and (ii) establishing new stations. In 2012, when the PEEX Program was initiated, it was evident that one of the main focus areas of interests would be filling the observational gaps, especially over the Siberian region, and the development of coordinated in situ observation networks across the Northern Eurasian region and in China. The backbone of the station network is based on the existing atmospheric, biosphere-ecological or urban stations. The first step towards a coordinated, comprehensive observation network is an overview of the measurement capacity of the existing stations in Russia. After gaining detailed information (station metadata) it would be also possible to make specific station upgrading plans, including and having adding new instruments and measured variables to the observing program of the station.

The collection of the preliminary information of the existing station activities started in 2012. The first inventory on over 200 in situ stations operating in the Arctic and Subarctic Eurasian regions was conducted by the Russian Academy of Sciences (RAS) and Moscow State University together with the University of Helsinki. Based on the first inventory we started a collection of more detailed information, called “station metadata”. Station metadata, the detailed descriptions of measured variables and the observation site, enables categorizing the stations in a systematic manner, connecting them to international observation networks, such as the WMO-Global Atmospheric Watch Program and the China Ecosystem Network (CERN), and standardizing data formats. The Russian station metadata collection has been carried out in 2016-2017 and continues in 2018. So far our database covers metadata from 53 stations.

As an INTAROS contribution, the metadata has been received from 11 measurement stations located within the Russian Arctic territories (see Figure 38). At these stations, long-term continuous measurements for temperature profiles of the soil/peat layers and soil/peat temperature profile down to the bedrock (borehole) are performed.

The programme of measurements is realised by the Earth Cryosphere Institute, Siberian Branch, Russian Academy of Sciences SB-RAS (for the Urengoy - sourthern forest-tundra, Urengoy-southern tundra, Kashin, Bolvanskiy, Marre-Sale, and Belyy, and Heiss Island stations); by the University of Eastern Finland, Kuopio, Finland and Institute of Biology, Komi Science Center, Syktyvkar, Russia (for Seida Vorkuta); by the P.I. Melnikov Permafrost Institute, SB RAS (for Igarka GeoCryLab, Tiksi); and by the Pacific Geographical Institute, Far Eastern Branch, RAS (for Chersky) whom are the owners of the stations. These measurements at the sites represent more local conditions of the immediate surrounding environment. Data (datasets/ data collections/ time-series of measurements) are available by request from the owners though direct contacts with the responsible persons (INTAROS questionaries A & B). At each station, data are stored (as txt-format files) in a personal repository (hard-disk, computer, notebook, etc.) and then later at the institutional level. At present, limited information on uncertainty arising from systematic and random effects in the measurements is available. More detailed information on PEEX and the station metadata is available by request (https://peexdata.atm.helsinki.fi).

Figure 38: Geographical positions of the selected 11 PEEX Russian Arctic stations (as a contribution to the INTAROS project).

Comprehensive and quality-controlled measurements (with automated & semi-automated loggers for measurements and for accumulating the data) are performed.

PEEX will demonstrate separate data analysis for Russian stations on a "showcase" basis by bilateral agreement between the PEEX Program and the station in question. Based on the metadata inventory PEEX will publish a station catalogue introducing the measurements and contact information of the "Russian stations - PEEX collaboration network". The aim of the catalogue is to promote the research collaboration, indicate the station as a partner in the Russian stations - PEEX collaboration network and to give positive visibility to the station activities.

2.11. GFZ

2.12.1. Airborne observations of surface-atmosphere fluxes

The data were derived during three aircraft AIRMETH (Airborne Measurements of Methane Fluxes) campaigns (Kohnert *et al.*, 2014) that aimed at capturing exchange processes between the surface and the atmosphere across large arctic permafrost landscapes. From the data obtained during the campaigns, fluxes of methane (CH_4), carbon dioxide (CO_2), as well as latent and sensible heat were derived via the eddy covariance technique.

Study areas

The AIRMETH campaigns took place in two study areas (Fig. 39). In each of the three four-week campaigns the approximately first two weeks were spent on the North Slope of Alaska, before crossing to the Mackenzie Delta in the Canadian Arctic for the second phase. In Alaska the base for the science flights (Fig. 39b) was the town of Utqiaġvik (formerly Barrow) located on the North Slope of Alaska. In the Mackenzie Delta the base was the town of Inuvik. The flights (Fig. 39c) were performed across the Mackenzie Delta, along the adjacent Yukon coastal plain towards Herschel Island, and on Richards Island north-east of the delta.

Campaign setup and instrumentation

On the North Slope, the study periods were 28 June to 02 July 2012 (5 flight days, 44 flight tracks), 04 July to 14 July 2013 (8 flight days, 43 flight tracks), and 25 August to 03 September 2016 (5 flight days, 16 flight tracks).

In the Mackenzie Delta, the study periods were 04 July to 10 July 2012 (5 flight days, 44 flight tracks), 19 July to 26 July, 2013 (7 flight days, 40 flight tracks), and 07 September to 20 September 2016 (8 flight days, 50 flight tracks).

Measurements were conducted aboard the research aircraft Polar 5 (Fig. 40) of the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Sciences (AWI). A science flight consisted of horizontal flight tracks in about 40 – 80 m above ground level at a true airspeed of 60 ms^{-1} for flux measurements (Fig. 40b) and vertical profile flights at the beginning and end of each low-level leg to determine the height of the atmospheric boundary layer via relative humidity and potential temperature.

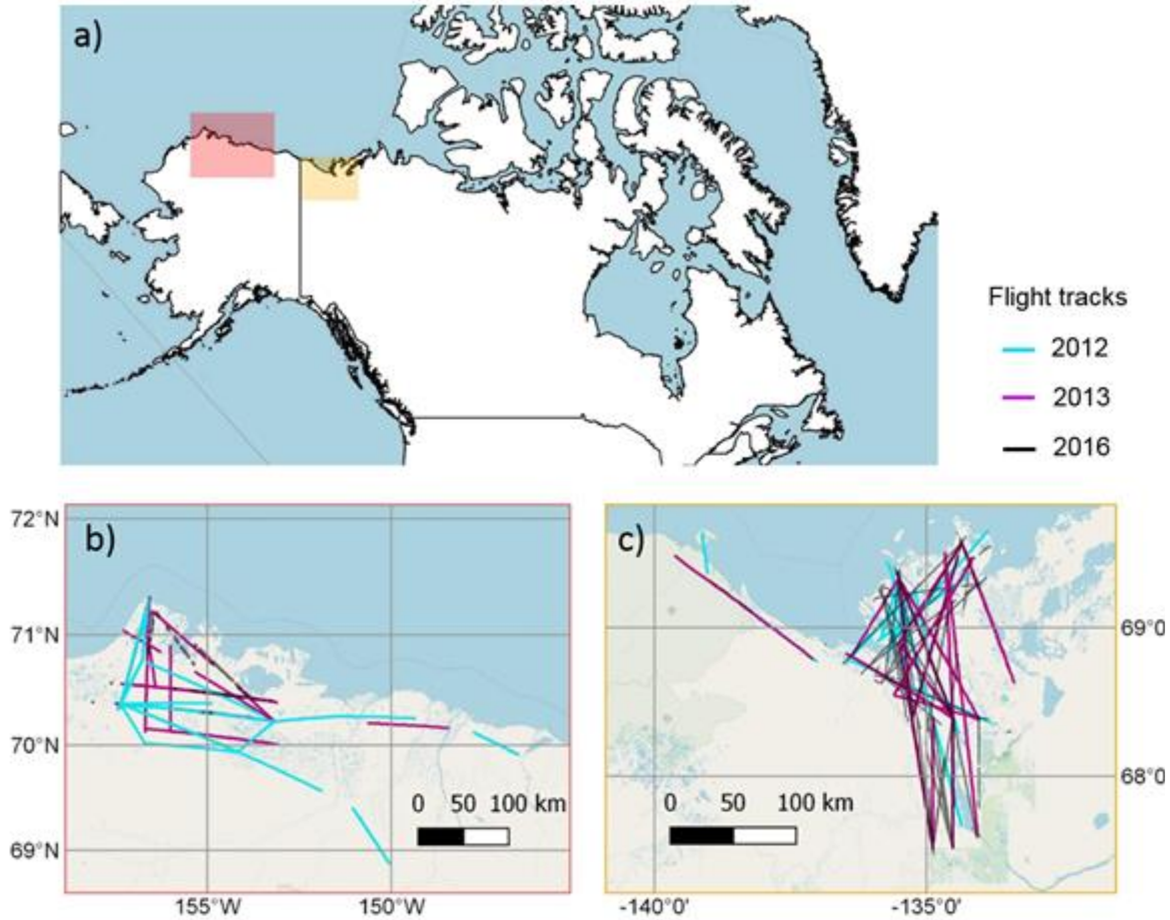

Figure 39. (a) Location of the study areas of the AIRMETH campaigns and flight tracks (b) on the North Slope of Alaska and (c) in the Mackenzie Delta area in Canada.

A 3 m nose boom including a Rosemount 5-hole probe for measuring the 3D wind vector at 100 Hz was mounted to the front of the airplane. Sample air was drawn from an inlet tube above the cabin at about 9.7 l s^{-1} and analysed at 20 Hz in an RMT-200 (Los Gatos Research Inc., Mountain View, California, USA) in 2012 (CH_4 concentration only) and in a Fast Greenhouse Gas Analyser FGGA 24EP (Los Gatos Research Inc.) in 2013 and 2016 (CH_4, CO_2 and water vapour). Additionally, the aircraft was equipped with an Inertial Navigation System (Type Laseref V, Honeywell International Inc., Morristown, New Jersey, USA), several Global Positioning Systems (NovAtel Inc., Calgary, Alberta, USA), a radar altimeter (KRA 405B/ Honeywell International Inc., Morristown, New Jersey, USA) and a laser altimeter (LD90/ RIEGL Laser Measurements Systems GmbH, Horn, Austria). Air temperature was measured with an open wire Pt100 in an unheated Rosemount housing, and air humidity with an HMT-330 (Vaisala, Helsinki, Finland) placed in a Rosemount housing. Flights above the ABL were excluded from flux calculations as well as data derived before the warm-up phase of the gas analyzer.

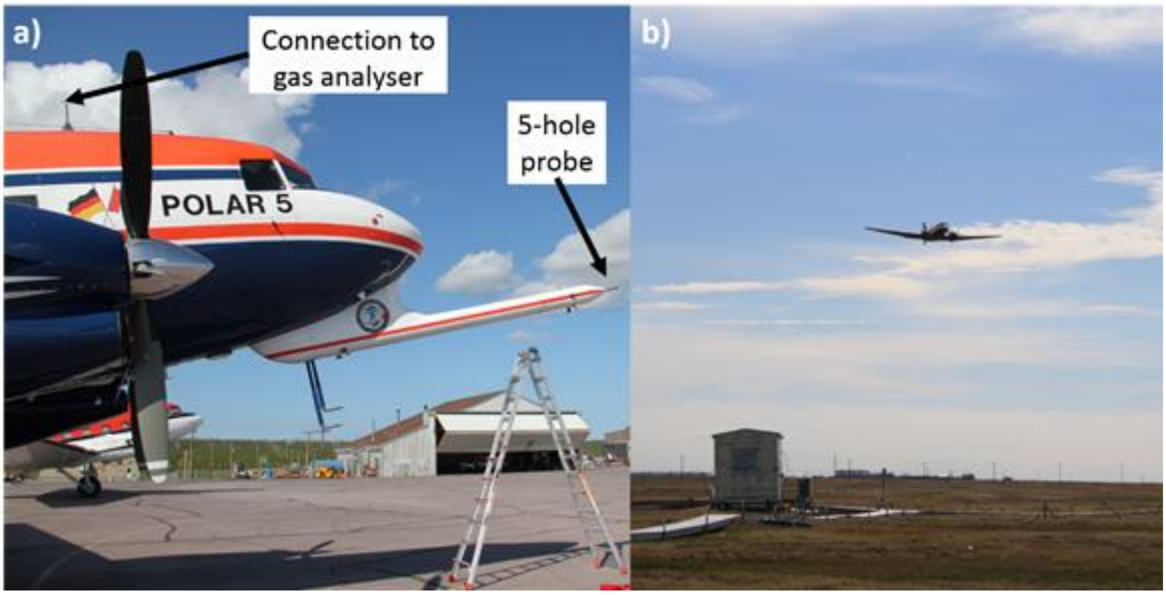

Figure 40 (a) The research aircraft Polar 5 as equipped during the AIRMETH campaigns and (b) depicted during a low level flight across the North Slope of Alaska.

Flux calculations

As described in Kohnert et al. (2017) we derived the wind components u, v, and w with respect to the earth coordinate system following the method suggested by Lenschow (1986). The data were analysed in GNU R version 3.3.1 using an (early) version of the eddy4R software (Metzger *et al.*, 2017). The analysis of the CH_4 fluxes was based on 20 Hz dry mole fraction data. We calculated the dry mole fraction by using the humidity information from the Vaisala HMT-330 in 2012, and that from the Fast Greenhouse Gas Analyser (Los Gatos Research Inc.) itself for the 2013 and 2016 data. Spectroscopic correction of the CH_4 concentration data was done following Tuzson *et al*. (2010). The fluxes were calculated with a time-frequency-resolved version of the eddy covariance technique, via wavelet analysis, using vertical wind speed and CH_4 concentration data (Metzger *et al.*, 2013). The result was an in situ observed space-series of the surface-atmosphere exchange of CH_4, CO_2, sensible and latent heat at 100 m spatial resolution (Fig. 41). With a footprint model modified after Kljun *et al*. (2004) as described in Metzger *et al.* (2012) and Metzger *et al.* (2013) the CH_4 emissions were related to the underlying surface. A height dependency of surface fluxes was not considered during these calculations. The data were quality controlled (Foken, 2008) and only data up to flag 6 (steady state and integral turbulence characteristics test ≤ 100 %), the upper threshold for data that are considered eligible for long-term measurements, should be included in an analysis. Uncertainties originate from the instrumentation and flux calculation.

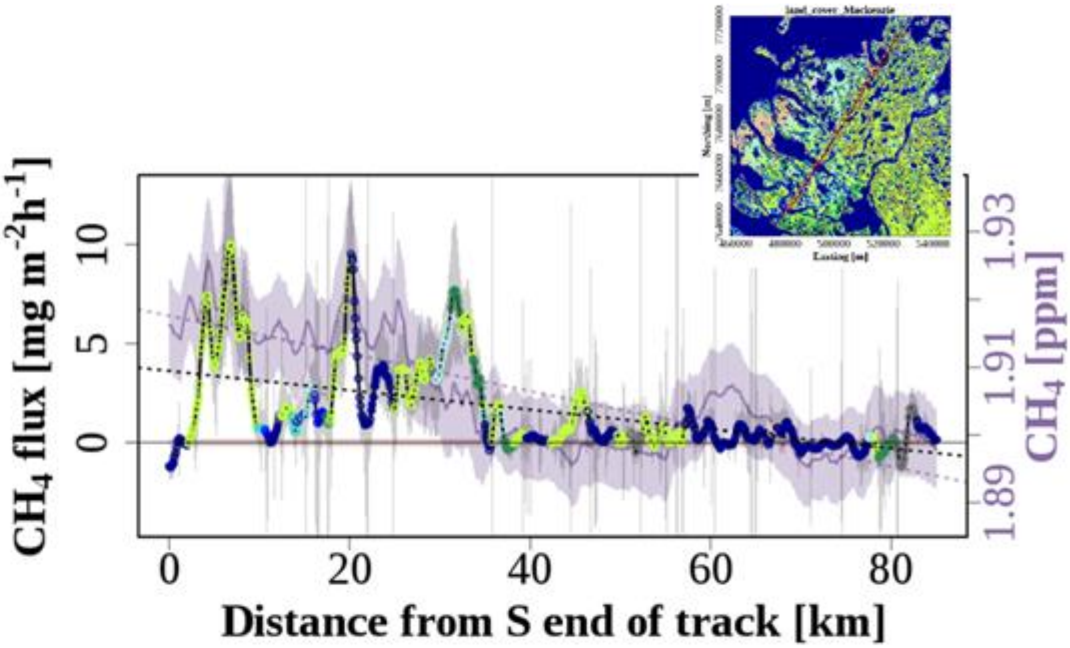

Figure 41. Example of the CH_4 fluxes along an approximately 85 km long flight track in the Mackenzie Delta (see small inlet figure). The CH_4 flux along the flight track is colored in blue and green, which represent the dominant land cover classes along the flight track. The purple line shows the CH_4 concentration and the shaded area the standard deviation of the CH_4 concentration. The dashed black line shows the trend of the CH_4 flux and the dashed purple line the trend in CH_4 concentration.

2.12. IGPAN

2.12.1. Snow measurements at the Polish Station Hornsund (Svalbard)

In situ measurements of snow depth in Spitsbergen are rare. The data are available only from a few sites. At the Polish Polar Station Hornsund (77°00′N, 15°33′E) meteorological site managed by the Institute of Geophysics, Polish Academy of Sciences, snow depth has been monitored at the same points since August 1982 and it constitutes the longest complete dataset (without any gaps) in Spitsbergen. Snow depth is calculated from a mean of three snow stakes and is measured together with snow water equivalent. Temporal variations of seasonal snow cover, and the duration and timing of snow accumulation and snowmelt induce feedbacks on many environmental components, and are crucial factors in the yearly cycle of land ecosystem. Later snow onset date, shorter duration and decrease of maximum depth are recently observed at Hornsund. The tendencies of changes in air temperature and precipitation can explain changes in snow cover. Increases in air temperature results in later development and shorter duration of snow cover. Despite a positive trend in precipitation at Hornsund in the period from second part of September through the first part of November, a negative trend in snow depth was estimated. This contradictory trend can be attributed to the observed increase in air temperature, which should directly impact the phase of precipitation. Recently more liquid or mixed precipitation in autumn during longer periods with positive air temperatures is observed.

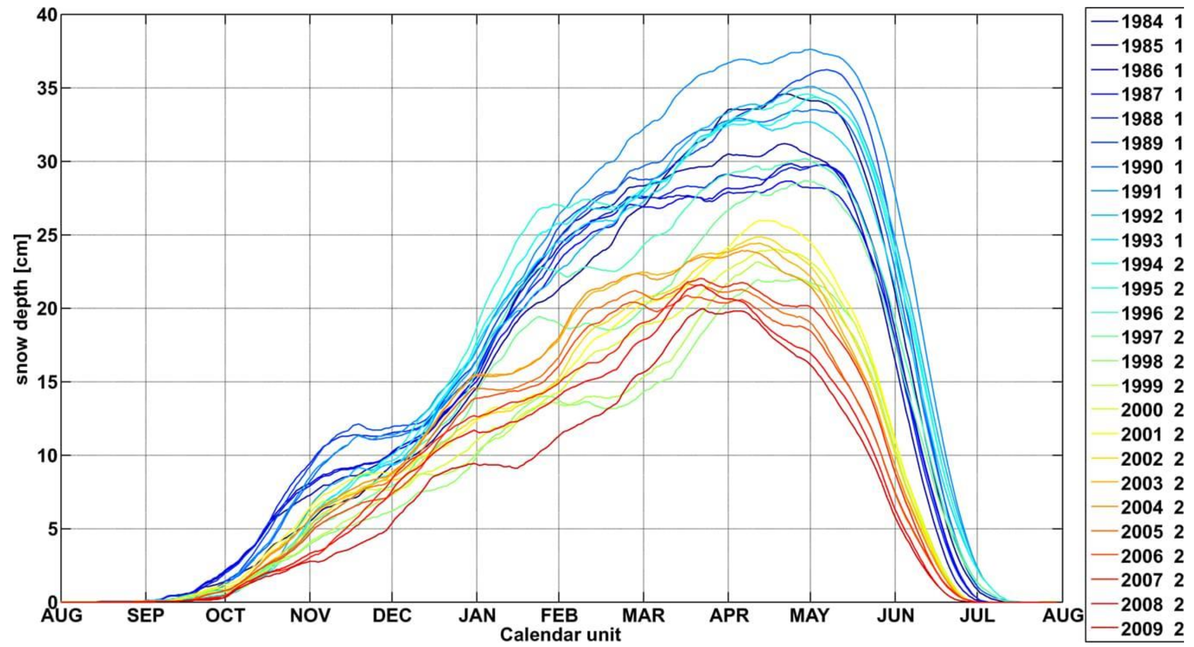

Figure 42. Visual representation of the Moving Average over Shifting Horizon (MASH) results for daily snow depth at the Hornsund station. The original time series covers the period N y = 32 snow seasons, from 1984/85 to 2015/16; therefore, MASH is composed of N h = 26 horizons. Each series represents a 7-year average of daily snow depth beginning in the year indicated (from Osuch, M., & Wawrzyniak, T., 2017).

The spatial distribution of snow depth and density in the Fuglebekken catchment located near the Hornsund Station is provided from year-round measurements managed by Station's personnel and time-lapse cameras. These measurements started in 2013 as an additional snow monitoring program and comprise a weekly survey of 20 points when a continuous snow cover is present on the ground. The depth is read from snow stakes (installed in 2013), while the average density and the snow water equivalent (SWE) are measured by weighing snow samples obtained with a 60 cm long tube close to the stakes. The data collection depends on weather conditions which result in extended gaps between measurements during period of unfavorable weather. The measurements are generally performed until the snow completely disappeares from the location of the point. Snow cover in Hornsund is continuously modified by wind drift, mostly caused by a strong easterly wind.

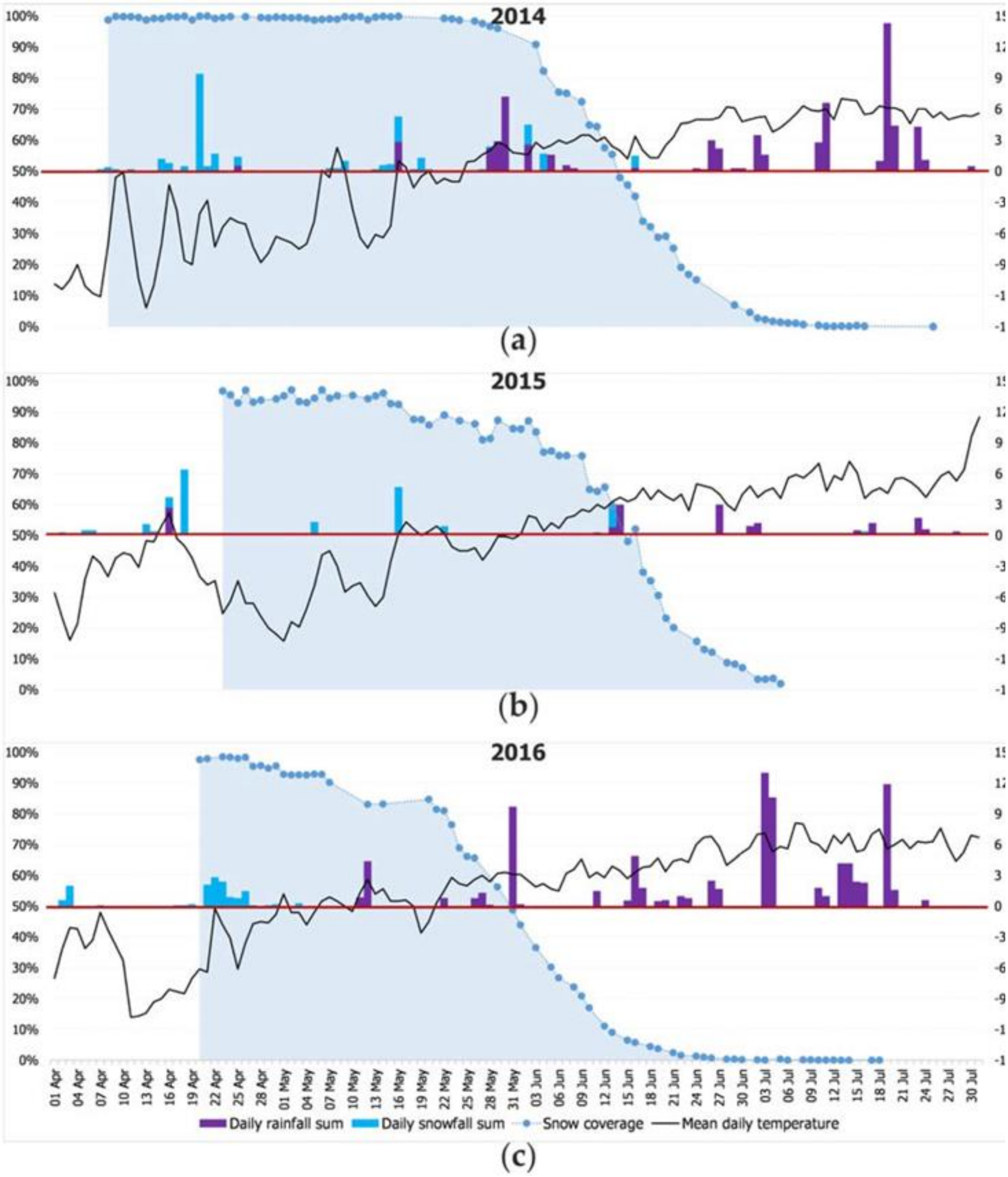

Figure 43. Evolution of snow cover extent in Fuglebekken catchment obtained from the time-lapse camera images in spring (a) 2014, (b) 2015 and (c) 2016; each blue point represents a classified image, daily meteorological data are shown in the background. (from Kępski et al., 2017)

2.13. U Slaski

2.13.1 Snow cover – Hornsund glaciers

A snow depth data series containing records obtained by high frequency GPR on selected glaciers of Hornsund area (S Svalbard) has been established since 2008. Currently the largest collection regards Hansbreen. Data for other glaciers are successively appended. The GPR survey on Hansbreen is regularly carried out approximately along the same tracks. Due to the dynamically changing glacier surface topography which influences different survey abilities some parts of the profiles are modified in consecutive seasons. The total distance of the Hansbreen profiles are (Fig. 44): 63.9 km (2008), 117,4 km (2011), 109,9 km 2013), 105,1 km (2014), 98,5 km (2015), 91,1 km (2016) and 101,0 km (2017).

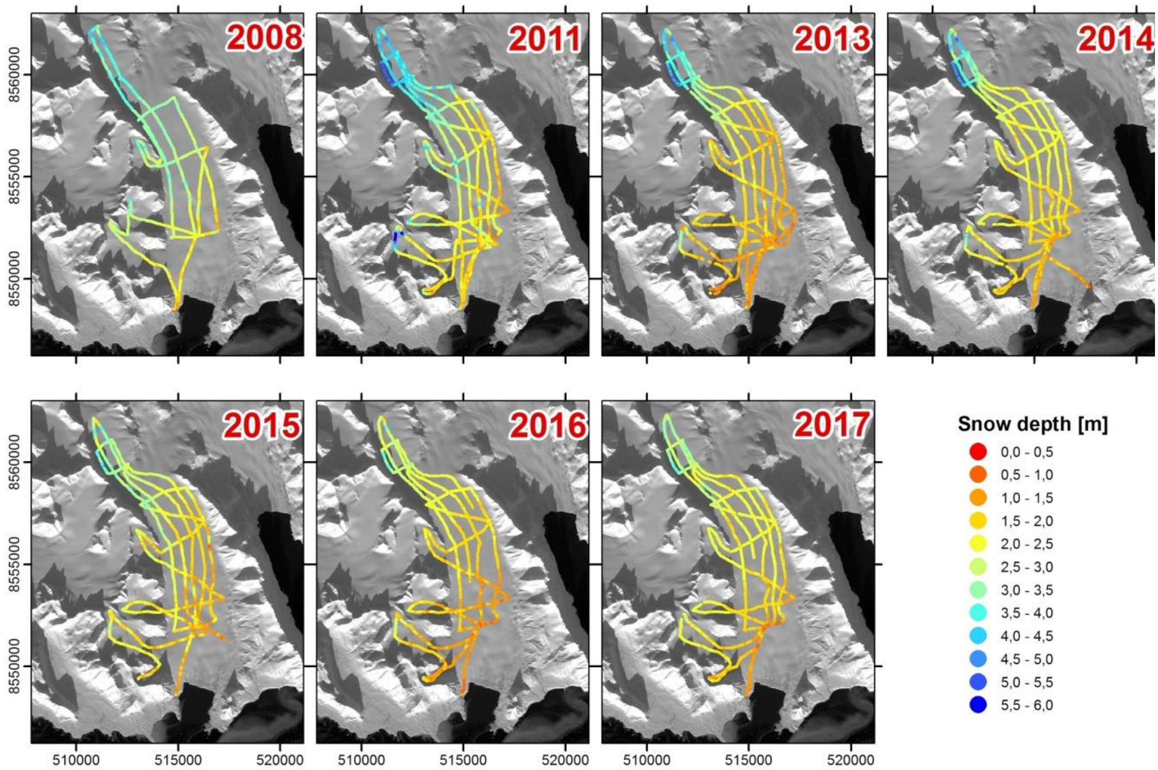

Fig.44. Snow distribution on Hansbreen at the end of accumulation seasons 2008 - 2017

An 800 MHz shielded antenna used in the GPR survey was fastened to the pulka, whereas the control unit and data collection system were placed on the sledge in the front. The measuring set was pulled behind the snowmobile and permanently controlled by the operator. The radar impulse had a constant repeat interval of 0.2 s (or 0.1 s in some detailed experiments carried out in 2011) which translates on average trace to a distance of c. 1.08 m (s.d. 0.44) (Grabiec 2017). The applied time window was around 80 ns with 1024 samples per trace (other sampling settings are possible) (Grabiec 2017). Most coordinates of the GPR traces were determined by dual-frequency GPS in postprocessing with average s.d. in XY and Z planes of 0.030 m and 0.100 m respectively (Grabiec 2017). On Tuvbreen and Deileggbreen exceptionally in 2013 when precise positioning was not available due to technical problems, the coordinates of navigation class have been used (Grabiec 2017).

The collected GPR data have been processed including coordinate correction, DC removal, time-zero correction, bandpass filtering and signal amplification. Then the time data have been converted into depth scale by applying a radiowave velocity (RWV) 0.21 m ns^{-1} (Grabiec et al. 2011) (see Fig. 45). Time-to-depth conversion was validated by comparing snow depth retrieved from radio echo-sounding data with in situ snow pits (Laska et al. 2017, Grabiec

2017). As snow records obtained by different methods were usually collected not exactly in the same time and place, depth differences of a few centimetres are acceptable.

The ice-snow interface in the GPR profile was determined semi-automatically. The function used connects points marked along the same phase of consecutive traces. The accuracy has been estimated as the average standard deviation from five times repeated selection of the ice-snow interface along the GPR profile from the front to the ice divide on Hansbreen in 2011 (along black dotted line on Fig. 45). The average s.d. along the profile was 0.51 ns (0,053 m); in ablation area: 0.43 ns and increased to 0.62 ns in accumulation zone (Grabiec 2017). Larger uncertainty in snow depth determination refers to areas where the snow base is ambiguous, e.g. crevassed areas filled with snow, superimposed ice and percolation zones and, in general, accumulation areas. The snow depth accuracy is also affected by the GPR vertical resolution that is 0.066m (taken as ¼ of the wavelength). The description of the data collection and processing is after Grabiec (2017).

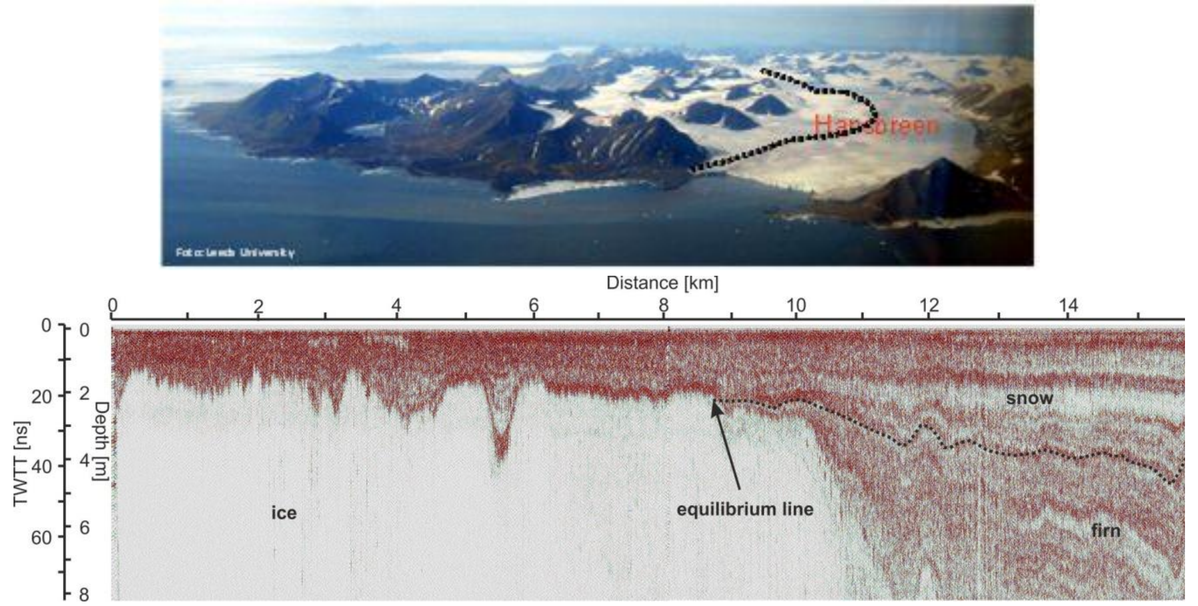

Figure 45. A sample GPR profile (800 MHz) from 2011 along black dotted line marked on picture (after Grabiec 2017, modified)

2.13.2 Front velocity of tidewater glaciers

The front velocity of tidewater glaciers in Hornsund was measured at one year intervals on stakes mounted at the glacier front. On Hansbreen, the position of stake Z was measured with dGPS technique (Leica GPS RTK GX1230GG) between August 2013 and August 2014. The accuracy of measurements with dGPS technique is ca. 5 cm.

On Hornbreen the positions of two stakes (T and U) were measured between August 2014 and August 2015 with a single-frequency GPS (Garmin 62). The annual glacier velocity on stake R on Storbreen was measured with a single-frequency GPS (Garmin 62). The accuracy of measurements with the GPS technique is a few meters.

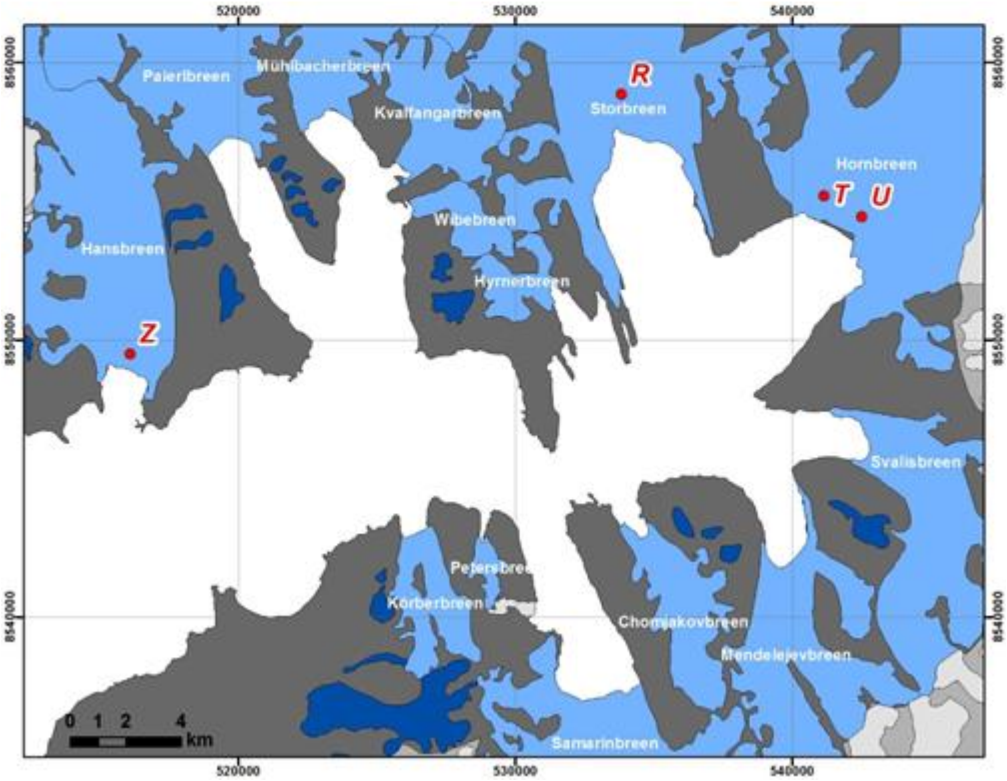

Figure 46: Red dots and capital letters - stakes positions on tidewater glaciers in Hornsund, measured with GPS.

2.14. Norut

2.14.1. Aerial measurements of surface properties on Svalbard

Norut has, in collaboration with Lufttransport AS and SIOS Infranor, established an airborne measurement platform by instrumenting a pod that will be permanently attached to the Dornier DO228, LN-LYR, one of the two Dornier aircraft owned and operated by Lufttransport and used for transport of cargo and personnel between Longyearbyen, Ny-Ålesund and Svea. This infrastucture is currently under establishment and is expected to become operational august 2018. The instruments consists of an aerial camera, hyperspectral imager and an X-band SAR, in addition there are sensors for supplying the needed metadata i.e. INS and GPS systems.

Geographical area: Regular coverage Longyearbyen-Kongsvegen-Ny-Ålesund and Longyearbyen -Svea. Irregular coverage on a demand basis.

Instruments and parameter(s) observed:

- *Aerial Camera*
- Data collected: High resolution RGB imagery.
- Derived Products: Snow cover, aerial maps, orthophotos
- *Hyperspectral imager*
- Data collected: spectral radiance, 180 bands between 400 and 1000nm, 3.3 nm sampling spacing

- Derived Products: Vegetation maps, NDVI, snow spectral albedo, snow grain size
- *X-band SAR*
- Data collected: Raw co-polarized SAR data
- Derived Products: Glacier facis; wet snow maps

Data management: Data are stored in an institutional repository. The data will be described and available for discovery though the SIOS portal. The data will be updated regularly, but in the starting phase it will take some time for cal/val, QC of products to be conducted and documented prior to release of data.

3. Requirements

The purpose of this section is to define the requirements used in the gap analysis (Section 4) of the observation systems, in-situ data collections, and satellite products.

3.1 In situ observing systems

Requirements for the in situ observing systems are set for the spatial and temporal coverage of the systems, and are defined with respect to the scientific and/or monitoring purposes of the systems. For instance, the requirement on spatial coverage of a network established to monitor a specific area (e.g. Greenland) is defined on the basis of the spatial extension and representativeness needed for the network to fulfil its goal. In practice, each observing system has constraints due to technical, practical, economical and political reasons, which will affect the degree in which they can achieve their goals (this "gap" between goal and actual achievement is evaluated in Sect. 4). Depending on the individual cases, the requirements of the observing systems can be qualitative or quantitative. Requirements for the specific data collections included in an observing system are quantified in section 3.2 and 3.3 and will add to the assessment of the system.

Table 1. Requirements for the in situ observing systems.

Observing system	App. area	Spatial coverage	Temporal coverage (length of the record, breaks)	Conf Level (1)	Source (name of the person defining the requirement)	Comment
Fluxnet (CO_2 & CH_4 FLUX)	Climate change analysis, time series analysis	Pan-Arctic	20-40 years	firm	Donatella Zona (USFD) Walter Oechel(U Exeter), Mathias Goeckede (MPG)	Min 20 years because the temporal coverage for the statistical analysis of the temporal changes need to include at least one AO or NAO cycle. Min 40 years because this would be the minimum requirement for a time series analysis of climate and flux data.
Fluxnet (CO_2 & CH_4 FLUX)	Climate model calibration	Pan-Arctic	7-10 years	reasonab le	Donatella Zona (USFD) Walter Oechel(U Exeter), Mathias Goeckede (MPG)	7-10 years to capture some interannual variability, and allow performance of some regression analysis; a longer dataset would be beneficial for this purpose, but not as critical as the one required for a time series analysis.
Airborne observations of surface-atmosphere fluxes	Climate change analysis	One study area in each mayor arctic zone (Alaska, Canada, Russia, Europe)	20 years with flights at least every second year (including spring/autumn campaigns)	firm	Katrin Kohnert (GFZ)	Min 20 years including spring and autumn campaigns to capture annual changes in the regional patterns
Airborne observations of surface-atmosphere fluxes	Climate model calibration	One study area in each mayor arctic zone (Alaska, Canada, Russia, Europe)	10 years with flights at least every second year including spring/autumn campaigns	firm	Katrin Kohnert (GFZ)	Include spring/autumn measurements to capture intra-annual and interannual changes in the regional patterns. Longer timespan would be beneficial
WGMS FoG database	Glacier dynamics modelling Climate and climate change studies Sea-level rise studies	Pan-Arctic	Minimum 10-20 years	reasonabl e	Francisco Navarro (UPM)	Minimum 10-20 years because it is the minimum required to detect changes in surface mass balance trends
GTN-G GlaThiDa database	Glacier dynamics modelling Climate and climate change studies Sea-level rise studies	Pan-Arctic	Good single measurement is sufficient	reasonabl e	Francisco Navarro (UPM)	With a single good (glacier-wide coverage sufficiently dense) radar survey, the ice-thickness distribution can be determined. Afterwards, thickness changes can be determined from surface elevation changes.
Randolph Glacier Inventory	Glacier dynamics modelling Climate and climate change studies Sea-level rise studies	Pan-Arctic	Single measurements repeated every 5 years (ideally every year)	reasonabl e	Francisco Navarro (UPM)	Calculation of glacier-wide mass balance requires proper outlines. Ideally this should be available for each annual SMB computation, but this is not realistic. 5 years can be a compromise solution providing sufficient accuracy.

Seismic monitoring	Operational services, geo-hazard forecast, research development	Pan-Arctic, evenly distributed stations in onshore and offshore areas.	Continuous and long-term (2-5 yrs)	firm	Mathilde Sørensen (UiB), Peter Voss (GEUS)	Long-term continuous monitoring is required to evaluate long-term seismicity rates and climate-induced seismicity rate changes. The network should be evenly distributed throughout the Arctic to assure reliable earthquake locations. This can only be achieved by including ocean bottom seismomenters (OBS) in the network to cover the offshore areas.
PEEX (Pan-Eurasian EXperiment), UHEL	Climate and climate change studies, ecosystem studies, time-series analysis	Arctic regions of Russia (north of 66.31N)	11 measurement stations in total; 4 stations have short 10 years time-series (the longer time series is the better, at least, 20-40 years)	reasonable	Hanna K. Lappalainen (UHEL), ALexander Mahura (UHEL)	Information on time series breaks is not available (contact with owners of the stations is required); observations to be used in climate, ecosystem, etc. research; considering the large area of the Russian Arctic territories it would be desirable to increase the number of the stations; long-term continuous measurements are needed
Polish Station-Hornsund (WIGOS 01003)	Climate and climate change studies, ecosystem studies, time-series analysis	Southern Spitsbergen	Long-term	firm	Piotr Głowacki (IGPAN)	Broader area of measurements for comparison
PROMICE	Climate research and monitoring	Greenland ice sheet ablation zone	>10 yrs at min. daily resolution required	tentative	GEUS	Determining the atmospheric near-surface climatology of the Greenland ice sheet ablation area
GC-Net	Climate research and monitoring	Greenland ice sheet accumulation zone	>10 yrs at min. daily resolution required (GC-Net: 1995-ongoing)	tentative	Konrad Steffen	Determining the atmospheric near-surface climatology of the Greenland ice sheet accumulation area
PROMICE	Research	Greenland ice sheet ablation zone	< 1 hr	tentative	GEUS	Process understanding of the surface mass balance of the ice sheet ablation zone
GC-Net	Research	Greenland ice sheet accumulation zone	< 1 hr	tentative	Konrad Steffen	Process understanding of the surface mass balance of the ice sheet accumulation zone
GNET (Greenland GPS network)	Research	Greenland	22 years	firm	DTU - Shfaqat Abbas Khan	surface ice mass change and bedrock deformation
Sodankylä supersite	Research	Sodankylä, Northern Boreal Zone	>20 years for climate studies	firm	Anna Kontu (FMI)	Carbon and water cycles in the Arctic
Arctic-HYCOS	Monitoring of river discharge fresh-water flow to the Arctic Ocean and related northern seas	Main river basins (>5000km2) covering >75% of the flow to ocean	>30 years	tentative	David Gustafsson (SMHI) -	The Pan-Arctic drainage basin includes all land areas draining to the Arctic Ocean and related northern seas as defined by the Arctic-HYCOS steering committee.
Arctic-HYCOS	Monitoring of hydrological regime in the pan-arctic drainage basin of the Arctic Ocean	Upstream river basins representing > 75% of the variability of	> 30 years	tentative	David Gustafsson (SMHI) - requirement translated from the objectives of the	The upstream river basins should represent the variability in land cover, topography, climate, soil, permafrost, and runoff characteristics at relevant spatial (basin area 10^2 - 10^6 km2) and temporal (daily, seasonally, annually) scales .

	and related northern seas	hydrological regimes			Arctic-HYCOS project	

(1) "Conf level" is applied as in the OSCAR database. It refers to the confidence with which the given requirement is trusted (e.g., "firm" when the value is a well-quantified goal in the pertinent community, "reasonable" when the value is quantified with robust arguments but it is not so widely applied as in the case of "firm", and "tentative" when the value is a first guess, based only on the experience of the person setting it).

3.2 In situ data collections and satellite products

Requirements for in situ data collections and satellite products are defined for data characteristics such as uncertainty and spatio-temporal coverage. Multiple sets of requirements for the same in situ data collection or satellite product can be defined depending on application areas (climate, operational services, environmental protection, geo-hazard forecast, research development, etc.) and target levels (goal, breakthrough, and threshold), as illustrated by the collection of requirements in the WMO OSCAR database (https://www.wmo-sat.info/oscar/requirements). When applicable, the requirements are extracted from the WMO OSCAR database and reported in Table 2. If the OSCAR requirements are inapplicable (because not suitable for ungridded data, or not tailored to the Arctic domain, or other reasons), other requirements are described (Table 3). In any case, a comment on the OSCAR requirements is given in Table 2, discussing whether they are valid for the planned application or not.

Table 2. WMO OSCAR requirements for the in situ and satellite-based data collections (ID refer to the WMO OSCAR database), with criteria level goal, breakthrough, threshold.

ID	Variable name	Layers	App. area	Uncert.	Horiz. res.	Vert. res.	Os cycle	Time-liness	Coverage	Conf Level	Comments
522	**River Discharge**	Land Surface	Ocean applications	0.01 $m^3 s^{-1}$ 0.05 $m^3 s^{-1}$ 0.1 $m^3 s^{-1}$	100 m 0.5 m 1 m		6 h 24 h 3 d	24 h 2 d 3 d	Global land	firm	The requirements seem to be relevant for gridded data and not for in situ measurements representing river discharge through a specific river section. Please note that the width of a river mouth can be several orders of magnitude larger than the horizontal resolution requirement here. In addition, the uncertainty requirement is completely unrealistic and close to the limit of detection. Type-error on the horizontal resolution (should it be 1km, 0.5km, 100m?) Timeliness and observational cycle requirements are more realistic for operational hydrological networks.
676	**River Discharge**	Land Surface	Climate-TOPC (deprecated)	5 $m^3 s^{-1}$ 7 $m^3 s^{-1}$ 10 $m^3 s^{-1}$	10 m 20 m 100 m		60 min 2 h 7 h	30 d 45 d 90 d	Global land	reasonable	In general, see comment on requirement 522. The uncertainty requirement is more realistic than in 522, but the horizontal resolution requirement is the same.
12	**Snow cover**	Land surface	CLIC (deprecated)	10 % 13 % 20 %	1 km 2.9 km 25 km		24 h 41 h 5 d	7 d 11 d 30 d	Global land	reasonable	
47	**Snow cover**	Land surface	Agricultural meteorology	2 % 4 % 10 %	1 km 2.2 km 10 km		5 d 6 d 7 d	24 h 44 h 6 d	Global land	reasonable	
108	**Snow cover**	Land surface	Climate-AOPC (deprecated)	10 % 13 % 20 %	100 km 200 km 500 km		24 h 2 d 7 d	6 h 12 h 24 h	Global land	firm	
220	**Snow cover**	Land surface	GEWEX (deprecated)	10 % 20 % 50 %	15 km 50 km 250 km		24 h 2 d 7 d	30 d 45 d 90 d	Global land	reasonable	
299	**Snow cover**	Land surface	Global NWP	10 % 20 % 50 %	5 km 15 km 100 km		3 h 24 h 5 d	3 h 24 h 5 d	Global land	firm	
375	**Snow cover**	Land surface	High res NWP	5 % 15 % 20 %	1 km 5 km 20 km		60 min 3 h 12 h	60 min 3 h 12 h	Global land	reasonable	
404	**Snow cover**	Land surface	Hydrology	5 % 8 % 20 %	0.1 km 1 km 100 km		24 h 46 h 7 d	24 h 44 h 6 d	Global land	reasonable	
446	**Snow cover**	Land surface	Nowcasting/VSRF	10 % 13 %	5 km 10 km		60 min 6 h	60 min 2 h	Global land	reasonable	

				20 %	50 km		24 h	6 h			
677	**Snow cover**	Land surface	Climate-TOPC (deprecated)	5 % 7 % 10 %	0.1 km 0.45 km 10 km		24 h 3 d 30 d	30 h 3 d 15 d	Global land	firm	
486	**Snow depth**	Sea surface	Ocean applications	0.005 cm 0.02 cm 0.05 cm	5 km 10 km 15 km		24 h 24 h 24 h	3 d 4 d 7 d	Global ocean	tentative	Probably unit of uncertainty should be m not cm. Now it doesn't make sense.
699	**Snow depth**	Land surface	Nowcasting / VSRF	0.1 cm 0.5 cm 2 cm	5 km 10 km 15 km		10 min 60 min 24 h	10 min 60 min 24 h	Global land	reasonable	Time limits are reasonable, but uncertainty of 0.1 cm is very difficult to reach. Now measured with 1 cm accuracy.
13	**Snow water equivalent**	Land surface	CLIC (dprecated)	10 % 20 % 50 %	5 km 15 km 100 km		3 h 24 h 5 d	3 h 24 h 5 d	Global land	firm	
48	**Snow water equivalent**	Land surface	Agricultural meteorology	5 mm 23.2 mm 500 mm	30 km 2.2 km 10 km		7 d 11 d 30 d	24 h 46 h 7 d	Global land	reasonable	Uncertainty of 500 mm should probably be 50 mm, which is still quite high.
109	**Snow water equivalent**	Land surface	Climate-AOPC (deprecated)	5 mm 6.5 mm 10 mm	100 km 200 km 500 km		24 h 2 d 7 d	6 h 12 h 24 h	Global land	firm	
221	**Snow water equivalent**	Land surface	GEWEX (deprecated)	5 mm 10 mm 20 mm	15 km 50 km 250 km		12 h 24 h 7 d	30 d 45 d 90 d	Global land	tentative	
300	**Snow water equivalent**	Land surface	Global NWP	2 mm 10 mm 20 mm	5 km 15 km 100 km		3 h 24 h 5 d	3 h 24 h 5 d	Global land	reasonable	
376	**Snow water equivalent**	Land surface	High res NWP	5 mm 8 mm 20 mm	0.5 km 2 km 20 km		60 min 3 h 6 h	60 min 3 h 24 h	Global land	tentative	
406	**Snow water equivalent**	Land surface	Hydrology	5 mm 8 mm 20 mm	0.1 km 0.464 km 10 km		24 h 46 h 7 d	24 h 44 h 6 d	Global land	reasonable	
758	**Snow water equivalent**		SSLP	5 mm 10 mm 20 mm	50 km 100 km 500 km		24 h 2 d 7 d	24 h 2 d 7 d	Global land	tentative	
29	**Soil temperature**	Land sufrace	Agricultural meteorology		5 km 7 km 19 km	-5, -10, -20, -50 and -100 cm	60 min 2 h 7 h		Global land		
522	**River Discharge**	Land Surface	Ocean applications	$0.01\ m^3\ s^{-1}$ $0.05\ m^3\ s^{-1}$ $0.1\ m^3\ s^{-1}$	100 m 0.5 km 1 km		6 h 24 h 3 d	24 h 2 d 3 d	Global land	firm	The uncertainty requirement is completely unrealistic. Timeliness and observational cycle requirements are more realistic compared to operational hydrological networks.
676	**River Discharge**	Land Surface	Climate-TOPC (deprecated)	$5\ m^3\ s^{-1}$ $7\ m^3\ s^{-1}$ $10\ m^3\ s^{-1}$	10 m 20 m 100 m		60 min 2 h	30 d 45 d 90 d	Global land	reasonable	See comment to requirement 522. The uncertainty requirement is more realistic here, but the

							7 h				horizontal resolution requirement is similarly unrealistic for in-situ observations.
401	**Permafrost (used for soil frost)**	Land surface	Hydrology	5 % 8.5 % 25 %	0.1 km 1 km 100 km		6 h 14 h 3 d	6 h 17 h 6 d	Global land	reasona ble	

Table 3. Non-OSCAR requirements for the in situ and satellite-based data collections.

Variable name	Layers	App. area	Uncert.	Horiz. res.	Vert. res.	Os cycle	Timeline ss	Coverage	Conf Level	Source (name of the person giving the requirement, or reference to literature)	Comments
Ice ablation	Ice sheet surface	Climate change research	0.05 m	n/a	n/a	1 hr	1 hr	Pan-Arctic	tentati ve	Andreas Ahlstrøm (GEUS)	This is the melting of the ice surface as it responds to the climate. The 1 hr OS cycle / timeliness is for potential geohazard applications
Temperature profiles of the soil/peat layers (PEEX, UHEL)	Soil /peat layers (depths of 0, 2, 3, 5 and 10 m)	Climate change and ecosystem research	0.1 C	at fixed locations	0, 2, 3, 5, 10 m	6 hr	Real time	Arctic regions of Russia (north of 66.31N)	reason able	Hanna K. Lappalainen, Alexander Mahura (UHEL)	not currently defined; still under discussion in the community
CO2 FLUX **(USFD, MPG, U Exeter)**	Land surface	Climate change analysis	1%	0.2-1km	Lower boundary layer	30 min	Real time	Pan-Arctic	firm	Donatella Zona (USFD), Mathias Goeckede (MPG), Walter Oechel (U Exeter)	not currently defined. Still under discussion in the community
CH4 FLUX (USFD, MPG, U Exeter)	Land surface	Climate change analysis	1%	0.2-1km	Lower boundary layer	30 min	Real time	Pan-Arctic	firm	Donatella Zona (USFD), Mathias Goeckede (MPG), Walter Oechel (U Exeter)	not currently defined. Still under discussion in the community
Snow depth (U Exeter)	Land surface	Climate change analysis	1%	1 m radius	Lower boundary layer	30 min	Real time	Pan-Arctic	unkno wn	Walter Oechel (U Exeter)	not currently defined. Still under discussion in the community
Airborne CO_2, CH_4, and heat flux	Land surface	Climate change analysis	30 %	100 m	Lower boundary layer	Twice a year annual Bi-annual	1 month 3 months 6 months	Pan-Arctic	firm	Katrin Kohnert (GFZ)	Horizontal resolution refers to the resolution of the CH_4 flux after the calculation, not the coverage with flight tracks. Uncertainty not currently defined. Still under discussion in the community

Airborne CO_2, CH_4, and heat flux	Land surface	climate model calibration	30 %	100 m	Lower boundary layer	Twice a year annual Bi-annual	1 month 3 months 6 months	Pan-Arctic	firm	Katrin Kohnert (GFZ)	Horizontal resolution refers to the resolution of the CH_4 flux after the calculation, not the coverage with flight tracks. Uncertainty not currently defined. Still under discussion in the community
Point snow density (winter, summer, annual)	Glacier snow cover	Glacier dynamics Climate change	10 kg/m3	n/a	n/a	1 year	1 year	Pan-Arctic	reasonable	Francisco Navarro (UPM)	Horiz. resol. does not apply to a variable, like snow density, that is representative of a certain area of undefined extent
Point SMB (winter, summer, annual)	Glacier surface	Glacier dynamics Climate change	0.2 m w.e.	n/a	n/a	1 year	1 year	Pan-Arctic	reasonable	Francisco Navarro (UPM)	Horiz. resol. does not apply to a variable, like point surface mass balance, that is representative of a certain area of undefined extent
Glacier-wide SMB (winter, summer, annual)	Glacier surface	Glacier dynamics Climate change	0.2 m w.e.	n/a	n/a	1 year	1 year	Pan-Arctic	reasonable	Francisco Navarro (UPM)	Horiz. resol. does not apply to a variable, like surface mass balance, that is integrated over a certain area (the glacier basin)
Glacier ice thickness	Glacier-covered land	Glacier dynamics Climate change	5%	20-30 m	5 m	n/a	< 1 year	Pan-Arctic	reasonable	Francisco Navarro (UPM)	Horiz. resol. typically 3-30 m for migrated radar data. For non-migrated data, it depends on the glacier thickness. Vertical resolution depends on the frequency of the radar used
Glacier outlines	Glacier-covered land	Glacier dynamics Climate change	5-10 m	5-10 m	n/a	n/a	< 1 year	Pan-Arctic	reasonable	Francisco Navarro (UPM)	Horiz. resol. typically 5-15 m, but can be up to 60 m.
Snow depth	Land surface	Glacier mass balance	0,01 m 0,05 m 0,10 m	140 m 320 m 500 m	n/a	1 d 1 m 1 y	7 d 1 m 1 y	Pan-Arctic	reasonable	Uncertinity: Østrem and Brugman (1991), other reqirements: M. Grabiec (USlaski)	Based on Østrem and Brugman (1991) satisfied snow depth density for mass balance purposes on valley glacier is 10-50 per 1 km^2 and less for ice caps
Glacier velocity	Land surface	Frontal ablation	1 m/y 5 m/y 10 m/y	n/a	n/a	1 d 1 m 1 y	7 d 1 m 1 y	Pan-Arctic	tentative	M. Błaszczyk (USlaski)	Horizontal and vertical resolution is not relevant for in-situ glacier velocity records. Data are collected in accessible part of glaciers for validation remote

											sensing glacier velocity data. At least one measurement site per glacier required.
Seismic ground velocity	Land or sea floor suface	Natural hazards like earthquakes or landslides	1ms	n/a	n/a	0.01s	real time	Pan-Arctic	firm	Peter Voss (GEUS), Mathilde Sørensen (UiB)	Uncertainty is for the timing if done using GPS.
glacier ice mass change	Land area	Glacier and ice sheet dynamics	0.003 m	n.a.	n.a.	24 h	real time	Greenland	firm	Shfaqat Abbas khan – (DTU)	The system measure land uplift due to ice loss
River discharge	River cross section	Fresh water inflow to Arctic Ocean	20%	n/a	n/a	1 d	1 d	>75% of the flow-to-ocean*	Tentati ve	David Gustafsson (SMHI	This is for the Arctic-HYCOS flow to Ocean network.
River discharge	River cross section	Climate change research	20%	n/a	n/a	1 d	1 d	>75% of variability in Arctic hydrological regimes	Tentati ve	David Gustafsson (SMHI	This is for the Arctic-HYCOS Hydrological regime network.

(1) "Conf level" is applied as in the OSCAR database. It refers to the confidence on which the given requirement is trusted (e.g., "firm" when the value is a well quantified goal in the pertinent community, "reasonable" when the value is quantified with robust arguments but it is not so widely applied as in the case of "firm", and "tentative" when the value is a first guess, based only on the experience of the person setting it).

4. Assessment of present observing capacities and gaps

In this section, a gap analysis of the observing systems and data collections described in Sect. 2 is performed. The analysis is separately done for the in situ observing systems (Sect. 4.1), for their data collections (Sect 4.2), and for the satellite products (Sect 4.3). The gaps in quantifiable characteristics such as spatial and temporal coverage, resolution, timeliness and uncertainty are estimated with respect to the requirements described in Sect. 3. The gaps in the sustainability and data management of the in situ observing systems and of the satellite products, as well as the gaps in metadata characteristics and description of the in situ data collections, are evaluated through maturity levels in a scale from 1 to 6. The highest level (6) corresponds to the highest maturity, which is the reference level for the gap analysis. Hence, the gaps are identified as the difference between the assessed and the reference levels.
The definition of the maturity levels for each of the assessed aspect of the data are provided in the in the GAIA-CLIM Measurement Maturity Matrix Guidance (Thorne et al., 2015) for the in situ data, and in Core-Climax System Maturity Matrix Instruction Manual (EUMETSAT, 2014) for the satellite products. They are also described in the questionnaires A, B, and C, the offline version of which can be found at https://intaros.nersc.no/node/651. In the following subsections, a synthesis of the level's definition is provided to facilitate the reader.

4.1 In situ and airborne observing systems

4.1.1 General information

The list of the assessed observation networks/systems, the addressed Arctic relevant variables (Essential Climate Variables (ECVs) and others), their data repositories, and the coordinating agencies are given in Table 4. The variables addressed in this assessment report are underlined.

Table 4. Terrestrial and Cryospheric in situ observing systems

Network or System (web link, if it exists)	Relevant Variables	Data assessor	Data Centres and Archives	Coordinating Bodies
Eddy covariance (short-tower) network of surface-atmosphere fluxes	• Carbon dioxide • Methane • and other long-lived greenhouse gases • Snow depth • Soil temperature	D. Zona (USFD), W. Oechel (U Exeter), M. Goeckede (MPG)	Fluxnet https://daac.ornl.gov/cgi-bin/dataset_lister.pl?p=9 (Ameriflux dataset are included in Fluxnet http://ameriflux.lbl.gov/)	Fluxnet (Ameriflux)
Airborne observations of surface-atmosphere fluxes	• Carbon dioxide • Methane • Water vapor • Air temperature • Wind speed and direction	K. Kohnert, A. Serafimovich, T. Sachs (GFZ)	No current data center	GFZ and AWI
Arctic-HYCOS Hydrological observation network	• River discharge	D. Gustafsson (SMHI)	• Global Runoff Data Centre (GRDC), Arctic Runoff Data Base (ARDB), Arctic-HYCOS (http://www.bafg.de/GRDC/EN/04_spcldtbss/41_ARDB/arcticHycos.html?nn=201698) • National Hydrological Services in Canada, Iceland, Finland, Norway, Russian Federation, USA, and Greenland	WMO CHy
World Glacier Monitoring System	• Snow • Ice sheets • Glaciers and ice caps	Francisco Navarro and M.I. Corcuera (UPM)	• National Snow and Ice data Center (NSIDC): http://nsidc.org/ • FMI Arctic Space Centre: http://litdb.fmi.fi/	UPM
Sodankylä observatory (Finland)	• Snow depth • SWE • Soil frost (temperature, dielectric constant)	Anna Kontu (FMI)	FMI Arctic Space Centre: http://litdb.fmi.fi/	FMI
PROMICE network (Greenland)	• Air temperature • Wind speed and direction • Water vapour	Andreas Ahlstrom (GEUS)	www.promice.org	GEUS

	• Pressure • Precipitation • Surface radiation budget • Ice ablation			
Greenland Ice Sheet Monitoring Network (GLISN)	• Earthquakes	Peter Voss (GEUS)	• http://www.glisn.info/ • ORFEUS - Observatories & Research Facilities for European Seismology: https://www.orfeus-eu.org/ • IRIS - Incorporated Research Institutions for Seismology: https://www.iris.edu	GEUS
Norwegian National Seismic Network (NNSN)	• Earthquakes	Mathilde Sørensen (UiB)	• skjelv.no • ORFEUS - Observatories & Research Facilities for European Seismology: https://www.orfeus-eu.org/ • IRIS - Incorporated Research Institutions for Seismology: https://www.iris.edu	UiB
Pan-Eurasian Experiment (PEEX) (https://www.atm.helsinki.fi/peex/index.php)	• Temperature profiles of the soil/peat layers, • Soil/peat temperature profile down to the bed rock (bore hole)	Hanna Lappalainen (UHEL), Alexander Mahura (UHEL)	• PEEX observing system metadata for stations are available at: https://peexdata.atm.helsinki.fi/; • Data collections / time-series are available under request from the owners (contacts are listed in questionnaire A) of the measurement stations	PEEX
Fluctuations of Glaciers Database (FoG)	• Glaciers and ice caps	Francisco Navarro and M.I. Corcuera (UPM)	• World Glacier Monitoring Service (WGMS) • http://wgms.ch/fogbrowser/	World Glacier Monitoring Service (WGMS) http://wgms.ch/
Glacier Thickness Database (GlaThiDa)	• Glaciers and ice caps	Francisco Navarro and M.I. Corcuera (UPM)	• World Glacier Monitoring Service (WGMS) • http://www.gtn-g.org/data_catalogue_glathida/	World Glacier Monitoring Service (WGMS) http://wgms.ch/
Randolph Glacier Inventory (RGI)	• Glaciers and ice caps	F. Navarro and M.I. Corcuera (UPM)	National Snow and Ice data Center (NSIDC) http://www.glims.org/RGI/index.html	National Snow and Ice data Center (NSIDC) http://nsidc.org/

Polish Station Hornsund in Svalbard (IGPAN)	• snow depth, • spatial snow cover, • SWE	Piotr Głowacki (IGPAN)	no current data centre	IGPAN
Greenland GPS Network (GNET)	• Glacier and Ice sheets mass change • Land uplift	Shfaqat Abbas Khan (DTU)	DTU	DTU

According to the respondents to the survey, 13 out of the 16 addressed in situ terrestrial observing systems do not have any risk of negative impact on the environment. One respondent (GNET - GPS networks) did not provide this information in the questionnaire. The remaining 2 terrestrial observing systems that possibly have some impact on the environment, the respondents checked if the interaction of the observing system with the environment is described by the indicators of "good environmental status" (defined by the European Commission: http://ec.europa.eu/environment/marine/good-environmental-status/index_en.htm), here slightly modified to be applied not just to the marine sphere but also to the atmosphere, terrestrial sphere, and cryosphere:

a. The observing system does not alter the biodiversity (The quality and occurrence of habitats and the distribution and abundance of species are in line with prevailing physiographic, geographic and climatic conditions).

b. The observing system does not introduce non-indigenous species that adversely alter the ecosystem (Non-indigenous species introduced by human activities are at levels that do not adversely alter the ecosystems. Non-indigenous species are species introduced outside their natural past or present range, which might survive and subsequently reproduce. These species are introduced in situations where exchange of people or goods takes place between countries and continents, by shipping for example)

c. The observing system does not affect the health of the population of commercially relevant animals (insects, birds, mammals, fishes).

d. The observing system does not alter any of the elements of food webs (All elements of the marine and terrestrial food webs, to the extent that they are known, occur at normal abundance and diversity and levels capable of ensuring the long-term abundance of the species and the retention of their full reproductive capacity).

e. Eutrophication introduced by the observing system in the nearby water bodies is minimized (Human-induced eutrophication is minimised, especially adverse effects thereof, such as losses in biodiversity, ecosystem degradation, harmful algae blooms and oxygen deficiency in bottom waters).

f. The observing system preserves the surface integrity (Surface integrity is at a level that ensures that the structure and functions of the ecosystems are safeguarded).

g. Contaminants introduced by the observing system are at a level not giving rise to pollution effects.

h. Properties and quantities of litter generated by the observing system do not cause harm to the environment.

i. Introduction of energy by the observing system does not adversely affect the ecosystem (by energy, we mean heat, noise, electromagnetic radiation, radio waves or vibrations).

The results are illustrated in Table 5.

In the case of Sodankylä supersite, reindeers have sometimes stuck to the cabling of the measurement system. The airborne observations of surface-atmosphere fluxes have been conducted during flight campaigns. The airplane/helicopter exhausts greenhouse gases.

Table 5. List of the indicators of good environmental status checked by the in situ atmospheric observing systems that possibly have negative impact with the environment. Respected indicators are marked with green and non-respected indicators are marked with red.

Indicators of good environmental status	**Sodankylä supersite**	**Airborne observations of surface-atmosphere fluxes**
The observing system does not alter the biodiversity		
The observing system does not introduce non-indigenous species that adversely alter the ecosystem		
The observing system does not affect the health of the population of commercially relevant animals		
The observing system does not alter any of the elements of food webs		
Eutrophication introduced by the observing system in the nearby water bodies is minimized		
The observing system preserves the surface integrity		
Contaminants introduced by the observing system are at a level not giving rise to pollution effects		
Properties and quantities of litter generated by the observing system do not cause harm to the environment		
Introduction of energy by the observing system does not adversely affect the ecosystem		

4.1.2 Spatial and temporal observation gaps

The spatial and temporal gaps in the observing systems are assessed through the comparison of their observational capabilities with the requirements listed in Sect. 3. The right column of Tables 6 and 7 describes the spatial and temporal observation gaps, respectively.

Table 6. Spatial coverage

Observing system	Spatial coverage of the observing system	Required spatial coverage	Comparison: observed vs required
Fluxnet (pan-Arctic gap analysis)	Currently 129 sites listed for domain >60°N	Ideally, all major Arctic ecosystems (boreal forest, and tundra) would be covered, therefore gaps depend on variability in ecosystem characteristics.	Considering the coverage of all eddy-covariance sites currently active in the high Northern latitudes, the biggest gaps are currently found in Russia, and some parts of Canada. However, this full data coverage is only available for CO_2 flux measurements in the summertime. Regarding our capability to monitor comprehensive exchange budgets of carbon between Arctic ecosystems and the atmosphere, the crucial elements that need to be extended are • measurements of CH_4 fluxes • measurements during the wintertime
Greenland Ice Sheet Monitoring Network (GLISN)	33 sites in and around Greenland	A higher number of sites provide more accurate results.	Offshore regions are underrepresented, North Greenland is underrepresented. Generally a higher number of sites will enable detection of seismic events of smaller magnitude and reveal more accurate information on source mechanisms.
Norwegian National Seismic Network (NNSN)	35 sites in mainland Norway, Jan Mayen, Svalbard, Bjørnøya and Hopen. 6 additional sites are under development in Svalbard. A new seismic array is being developed on Bjørnøya.	A higher number of sites provide more accurate results.	Offshore regions are underrepresented. Generally a higher number of sites will enable detection of seismic events of smaller magnitude and reveal more accurate information on source mechanisms.
PEEX (Pan-Eurasian EXperiment)	Arctic regions of Russia (northerly of 66.31°N)	More dense network of stations would be desirable along the longitudinal belt	Although stations are placed within the tundra environment, these are spaced at large distances from each other in longitude; increased number of stations with an enlarged programme of measurements would be desirable to have more dense spatial coverage of the Russian Arctic region; an optimisation task for calculating geographical positioning would be useful in order to have larger number of representative stations for the Russian Arctic region
Sodankylä Observatory (Finland)	Main operations in Sodankylä (67.37°N 26.63°E), measurements in Northern Finland and NH	Sodankylä/Northern Finland	Most measurements are located in FMI Sodankylä station, some cover wider areas. Station is a member of several networks, e.g. GCW, GAW, GRUAN, ICOS, INTERACT, TCCON.

Airborne observations of surface-atmosphere fluxes	AIRMETH|MULTIPOLYGON ((69.61 -140.76, 68.45 -136.07, 67.46 -135.30, 69.76 -133.36, 68.61 -133, 67.49 -133.89), (71.70 -156.51, 68.31 -167.1, 69.65 -141.26, 69.11 -147.87, 68.48 -154.33), (72.97 121.66, 74.1 123.29, 73.36 129.72, 72.09 129.61, 72.08 126.61))	One study area in each mayor arctic zone (Alaska, Canada, Russia, Europe)	Alaska represented with the North Slope of Alaska Canada represented with the Mackenzie Delta Russia: Reliable flux data from Lena Delta needed (in progress) Europe: Reliable and more aircraft data needed in Scandinavia
Fluctuations of Glaciers Database (FoG)	Pan-Arctic, covering homogeneously the following subregions of the GTN-G Glacier Regions catalogue: Alaska, Canadian Arctic North, Canadian Arctic South, Franz Josef, Greenland Periphery, Iceland, Svalbard & Jan Mayen, Mackencie, Novaya Zemlya, Severnaya Zemlya	Pan-Arctic, covering heterogeneously the following subregions of the GTN-G Glacier Regions catalogue: Alaska, Canadian Arctic North, Canadian Arctic South, Franz Josef, Greenland Periphery, Iceland, Svalbard & Jan Mayen, Mackencie, Novaya Zemlya, Severnaya Zemlya	Of a total of about 61,400 individual glaciers in the Arctic region, covering a total area of about 420,000 km^2, there are SMB series for 106 of them, but only 32 are maintained at present. Moreover, the geographical distribution is quite irregular. Iceland is, by far, the best covered area, while the Russian Arctic is the worst covered (with no coverage at present). Peripheral Greenland is poorly covered, and the Canadian Arctic is also under-represented, especially taking into account its large glaciated area. Most other regions are fairly well covered.
Glacier Thickness Database (GlaThiDa)	Pan-Arctic, covering homogeneously the following subregions of the GTN-G Glacier Regions catalogue: Alaska, Canadian Arctic North, Canadian Arctic South, Franz Josef, Greenland Periphery, Iceland, Svalbard & Jan Mayen, Mackencie, Novaya Zemlya, Severnaya Zemlya	Pan-Arctic, covering heterogeneously the following subregions of the GTN-G Glacier Regions catalogue: Alaska, Canadian Arctic North, Canadian Arctic South, Franz Josef, Greenland Periphery, Iceland, Svalbard & Jan Mayen, Mackencie, Novaya Zemlya, Severnaya Zemlya	Of a total of about 61,400 individual glaciers in the Arctic region, covering a total area of about 420,000 km2, there are ice-thickness data for about 1050 glaciers. However, the spatial coverage is very irregular. The regions with far more ice-thickness data are those that have been covered by airborne ground-penetrating radar campaigns (mostly by the IceBridge Operation). The Canadian Arctic, Peripheral Greenland and Svalbard & Jan Mayen are the best covered regions (about 1000 records in total), while the rest of the regions have in total just a few records (about 50).
Randolph Glacier Inventory (RGI)	Pan-Arctic, covering homogeneously the following subregions of the GTN-G Glacier Regions catalogue: Alaska, Canadian Arctic North, Canadian Arctic South, Franz	Pan-Arctic, covering heterogeneously the following subregions of the GTN-G Glacier Regions catalogue: Alaska, Canadian Arctic North, Canadian Arctic South, Franz	The coverage is total (pan-Arctic). There are available glacier outlines for each of the about 61,400 individual glaciers in the Arctic region. This has been possible thanks to the remote sensing satellite tools available nowadays.

	Josef, Greenland Periphery, Iceland, Svalbard & Jan Mayen, Mackencie, Novaya Zemlya, Severnaya Zemlya	Josef, Greenland Periphery, Iceland, Svalbard & Jan Mayen, Mackencie, Novaya Zemlya, Severnaya Zemlya	
PROMICE Automatic weather stations network	Point measurements mainly in the melt (ablation) zone of the Greenland ice sheet placed in different regions in Greenland	Regions in Greenland with different climate should be covered to represent spatial variability	Currently, a few regions may be under-represented, including SW Greenland (both north and south of Tasiilaq), N Greenland (around Humboldt and Petermann Glaciers), NW Greenland (central Melville Bay). These have been omitted for logistical /financial reasons.
Polish Station Hornsund	Snow measurements are located in the proximity of the station	Spatial representative of the local catchment area (minimum requirement) and of a larger terrestrial region (goal)	The measurements are sufficient to derive the snow variability in the station catchment area, but not for a larger area
Greenland GPS Network (GNET)	58 stations	70 stations	Good
Arctic-HYCOS river discharge	427 stations of which 80 can be used for flow-to-ocean estimation. The drainage basins of the stations cover 58% of the spatial domain and represent 56 % of the total estimated flow-to-ocean (63% and 61%, respectively if Greenland is excluded.	75% of the flow-to-ocean and 75% of the spatial variability in the Arctic hydrological regimes	The spatial coverage and the representation of the total flow to ocean is around 60% which might be good enough, but still somewhat lower than the tentative requirement (75%).

Table 7. Temporal coverage (temporal extension and breaks in system data collections)

Observing system	Temporal coverage of the observing system	Required temporal coverage	Comparison: observed vs required
Fluxnet (pan-Arctic gap analysis) (MPG, USFD, UExeter)	The largest number of sites was started between 2000 and 2010. Most sites do not offer continuous observations during wintertime	At least 10 continuous years of data coverage to allow detection of long-term trends; year-round measurements	Only few of the currently available Arctic eddy-covariance sites offer time series (>10 years) that allow analysis of long-term trends i.e. changes in carbon cycle processes that can be linked to climate change in the region. Therefore, funding support needs to be sustained to keep existing sites running, and extend datasets. Only few of the currently active sites offer continuous observations that include cold season fluxes. Since it has been shown recently that these months contribute a large share to the annual carbon budgets, the missing wintertime data in large parts of the Arctic constitute a crucial gap in our observational infrastructure. Therefore, sites should be improved to facilitate year-round measurements also under very harsh wintertime climate conditions.
PEEX (Pan-Eurasian EXperiment), (UHEL)	earliest start of time-series (among 11 stations) is from 1930 at Igarka GeoCryLab; measurements are performed following standard procedure	continuation of observations is needed; a shorter time interval between measurements would be desirable	At 4 measurement stations (Seida Vorkuta, Kashin, Belyy, Heiss Island) the duration of measurements (since 2007, 2008, 2009, 2010) is relatively short for climate related studies (more measurements are needed);
Sodankylä Observatory (Finland)	Snow measurements since 1 Jan 1908. First daily manual measurements, now monthly/weekly manual and 10 min automatic measurements.	Continuation of present observation to attain long time series (> 20 years) on variables such as surface radiation budget, precipitation, SWE, soil frost	100 years of daily air temperatures and snow depths available. Other parameters mostly from the 2000's. Early observations of winter precipitation and SWE with high uncertainty
Airborne observations of surface-atmosphere fluxes (GFZ)	2012/06 – 2012/08 2013/07 2014/04 – 2014/08 2016/08 – 2016/09	20 years with flights at least every second year (including spring/autumn campaigns)	Alaska, Canada and Russia campaigns started in 2012 with some repetitions since, but repetition of Russia campaigns is still limited

Airborne obs. of surface-atmosphere fluxes (GFZ)	2012/06 – 2012/08 2013/07 2014/04 – 2014/08 2016/08 – 2016/09	10 years with flights at least every second year including spring/autumn campaigns	Alaska, Canada and Russia campaigns started in 2012 with some repetitions since, but repetition of Russia campaigns is still limited
PROMICE Automatic weather stations network (GEUS)	Most of network operational since 2010. Measurement frequency is 10 min with substantially lower data transmission rate, especially in winter	Duration indefinite. Measurement frequency 1 hr is sufficient. Transmission rates should be once an hour for this parameter	In terms of duration, the AWS should be maintained indefinitely to follow decadal trends in climate variability. In terms of observation frequency, the current 10 minute rate is more than adequate. Generally, the transmission rate should be increased in the wintertime to obtain uniform transmission rates throughout the year with hourly transmissions as the goal. For potential geohazards applications the current 1 hr summertime transmission rate is sufficient, though.
Fluctuations of Glaciers Database (FoG) (UPM)	WGMS was initiated in 1986, but systematic and detailed collections of data start in 1959. Data are available for each mass balance (or hydrological) year.	Mass balance studies require yearly data, and the time series should be at least 10-20 year long to be useful for climate-related studies.	The temporal coverage provided by the available data is OK regarding frequency (annual mass balance data). However, time series of 10-20 yr length, required for climate-related studies, are rarely available in the Arctic region because of logistic difficulties and long-term sustainability of such long time series (e.g. due to limited duration of funding), unless the monitored glaciers are located close to Arctic permanent stations.
Glacier Thickness Database (GlaThiDa) (UPM)	The ice thickness data correspond to the period 01/01/1955-31/12/2015, but normally there is a single set of data per glacier, for a given time.	Ideally, there should be a set of ice thickness data every ca. 10 years.	Because ground-penetrating radar campaigns are logistically complex and costly, most glaciers have available a single set of measurements. However, if this set is sufficiently good, then ice thickness (and glacier volume) change can be more easily (and cheaply) monitored through surface elevation changes, which can be done using satellite remote sensing tools.
Randolph Glacier Inventory (RGI) (UPM)	Satellite imagery from 1999-2010 provided most of the glacier outlines, which correspond to a single time.	Ideally, there should be a set of glacier outlines every ca. 10 years.	So far there is available a single set of outlines for each of the about 61,000 individual glaciers in the Arctic. It would be convenient to repeat this kind of measurements every ca. 10 years. This should be possible with the currently-available satellite remote sensing tools.
Polish Station Hornsund	Continuous snow observations since 1982	➢ 20y for climate studies	Requirement fulfilled
Greenland Ice Sheet Monitoring Network (GLISN)	Most of network operational since 2009, with a groth in sites in Greenland	Continuous recording (100 Hz sampling) with real time data transfer.	Downtime mainly due to gaps in data transfer or instrument failure. Gaps can be in minutes or months.

Norwegian National Seismic Network (NNSN)	First station was installed in 1905. Denser station coverage since the 1980s, and still improving.	Continuous recording (100 Hz sampling) with real time data transfer.	Downtime mainly due to gaps in data transfer or instrument failure. Gaps can be in minutes or months, are mostly short.
Arctic-HYCOS river discharge	Average time series length is around 50 years and the longest more than 100 years.	More than 30 years	Requirement met.

4.1.3 Gaps in the observation variables

In Table 8 the essential atmospheric variables are listed, together with the in situ observing systems that measure them. The list includes the essential climate variables (ECV) and other variables relevant for various research and operational applications.

Table 8. Essential variables (not only ECVs) measured by the in situ observing systems

Terrestrial domain	Essential Variable	Observing systems measuring the essential variables
BIOSPHERE	Above ground biomass (above-ground living biomass (excludes roots, litter, and dead wood), Forest height)	• Greenland Ecosystem Monitoring program
	LAI (Leaf Area Index)	• SIOS Airborne Infrastructure
	Land cover (land cover classes, including vegetation type)	• Greenland Ecosystem Monitoring program • SIOS Airborne Infrastructure
	Land surface temperature	• Greenland Ecosystem Monitoring program • Airborne observations of surface-atmosphere fluxes; campaign basis; the growing seasons: 2012, 2013, 2014 and 2016; regions: a) North Slope of Alaska and b) the Mackenzie Delta in Canada and the adjacent Richards Island and the Yukon Coastal Plain and c) the Lena Delta in Siberia • Fluxnet
	Greenhouse gas concentrations (CH_4, CO_2, H_2O)	• Airborne observations of surface-atmosphere fluxes; campaign basis; the growing seasons: 2012, 2013, 2014 and 2016; regions: a) North Slope of Alaska and b) the Mackenzie Delta in Canada and the adjacent Richards Island and the Yukon Coastal Plain and c) the Lena Delta in Siberia
	Soil carbon (fraction of carbon in soil)	• Greenland Ecosystem Monitoring program
CRUST	Earthquakes	• GLISN network Greenland • Norwegian National Seismic Network (NNSN) • GNET - GPS networks

CRYOSPHERE	Glaciers (Area, elevation change, glacier mass change, glacier topography)	• Greenland Ecosystem Monitoring program • Polish Station Hornsund • SIOS Airborne Infrastructure • World Glacier Monitoring Service-Fluctuations of Glaciers Database • Glacier Thickness Database (GlaThiDa) • Randolph Glacier Inventory (RGI) • GNET - GPS networks
	Ice sheets (Surface elevation change, ice velocity, mass balance, grounding line location, ice shelf thickness, topography)	• Greenland Ecosystem Monitoring program • Greenland Climate Network (GC-Net) • PROMICE automatic weather station network • GNET - GPS networks
	Permafrost (depth of active layer, permafrost temperature)	• Greenland Ecosystem Monitoring program • WMO Integrated Global Observing System (WIGOS) - Regional Basic Synoptic Network (RBSN) - Hornsund 01003 (Polish Polar Station) • Fluxnet
	Snow (Spatial extent of snow, fractional snow cover (viewable and canopy adjusted), snow depth, snow water equivalent, snow grain size, snow impurity content (or radiative forcing by impurities))	• Greenland Ecosystem Monitoring program • WMO Integrated Global Observing System (WIGOS) - Regional Basic Synoptic Network (RBSN) - Hornsund 01003 (Polish Polar Station) • Greenland Climate Network (GC-Net) • Sodankylä supersite • Automated Weather and Snow Measuring System • SIOS Airborne Infrastructure • Fluxnet
	Albedo (Bidirectional reflectance factor (BRF), reflectance anisotropy (BRDF), bidirectional hemispherical reflectance under isotropic illumination)	• Greenland Ecosystem Monitoring program
ECOSYSTEMS	Greenhouse gas fluxes (CO_2, CH_4)	• Greenland Ecosystem Monitoring program • Sodankylä supersite • Airborne observations of surface-atmosphere fluxes; campaign basis; the growing seasons: 2012, 2013, 2014 and 2016; regions: a) North Slope of Alaska and b) the Mackenzie Delta in Canada and the adjacent Richards Island and the Yukon Coastal Plain and c) the Lena Delta in Siberia • Fluxnet
HYDROLOGY	Lakes (Lake water level, lake water extent, lake surface water temperature, lake ice cover, lake ice thickness, Lake snow thickness, lake colour)	• Greenland Ecosystem Monitoring program • SIOS Airborne Infrastructure

	River discharge (River discharge, water level, flow velocity, cross-section)	• Greenland Ecosystem Monitoring program • WMO Integrated Global Observing System (WIGOS) - Regional Basic Synoptic Network (RBSN) - Hornsund 01003 (Polish Polar Station) • Arctic-HYCOS
	Soil moisture (Surface soil moisture content, Freeze/thaw status, surface inundation, vegetation optical depth, root-zone soil moisture content)	• Greenland Ecosystem Monitoring program • Sodankylä supersite • Fluxnet

General considerations that can be made about the listed measured variables are:

- For the **land cover** we need a more specific set of cover types for the Arctic than appears in some land cover schemes. In particular, shrubs, mosses and water tolerant grasses/sedges need to be included.
- For **GHG measurements**: more measurements are needed in autumn/winter, in the discontinuous (or melting) permafrost zone, and in Siberia. Also, the GHG fluxes measurements need to be linked to simultaneous soil water status measurements and vegetation type/wetland type. These co-located measurements should be done in situ for the small (local) scale and from satellite for the larger scale (with the exception of permafrost, which should be monitored via in situ measurements).
- **Soil carbon** in the Arctic is the largest store of terrestrial carbon, but there are only very sparse measurements of it. However, addressing this would be highly labour, intensive and expensive and may not be practical. Still, it is a gap.
- The measurements of some key **snow variables** (such as snow depth, snow water equivalent, and snow grain size) are still mostly manual and time consuming. Snow grain size is very rarely measured, but time series across the snow season would be needed. Only very few sites do snow albedo measurements. These observations would be needed in much more sites.

4.1.4 Gaps in the observation accuracy

The main issue we want to address here is at which level the data collections belonging to the same observation system are uniform in uncertainty. We know, for instance, that the meteorological stations belonging to the IASOA and IGRA networks have different standards in uncertainty. An assessment of this uncertainty inhomogeneity is needed to evaluate benefits/costs in increasing the homogeneity of the uncertainty of the existing observing stations and platforms, against the benefits/costs of increasing the numbers of observing stations/platforms. The uncertainty assessment of each data collection, done in Sect. 4.2.3, is used here to evaluate the homogeneity of the uncertainty in the observing systems. The assessment is done through a score:

- Score 1: Only limited information on uncertainty is available for the system, as most of its data collections have answers (1) or (2) in question 6.5 concerning the uncertainty quantification (see Questionnaire B)
- Score 2: The system has high heterogeneity in data uncertainty: most of the assessed data collections have answers between (3) and (6) in question 6.5 concerning the uncertainty quantification (see Questionnaire B), but only less than 25% of the data collections reach the threshold level of uncertainty.

- Score 3: The system has high heterogeneity in data uncertainty: most of the assessed data collections have answers between (3) and (6) in question 6.5 concerning the uncertainty quantification (see Questionnaire B), but less than 50% of the data collections reach the threshold level of uncertainty.
- Score 4: The system reaches a discrete standard in data uncertainty: most of the assessed data collections have answers between (3) and (6) in question 6.5 concerning the uncertainty quantification (see Questionnaire B), and more than 50% of the data collections reach the threshold level of uncertainty.
- Score 5: The system reaches a good standard in data uncertainty: all the assessed data collections have answers between (3) and (6) in question 6.5 concerning the uncertainty quantification (see Questionnaire B), and most of the data collections reach the threshold level of uncertainty.
- Score 6: The system reaches an excellent standard in data uncertainty: all the assessed data collections have answers between (3) and (6) in question 6.5 concerning the uncertainty quantification (see Questionnaire B), and all the data collections reach the threshold level of uncertainty.

Table 9 illustrates the scores reached by the addressed observing systems: there is a dichotomy between about half of the observing systems that have none or limited information on the data uncertainty, and the other half that reaches the maximum score, meaning that all data collections have high standards in uncertainty characterization.

Table 9. Observing systems classified by the degree of heterogeneity in the uncertainty of their observations from score 1 to 6 (decreasing heterogeneity).

Score	In situ observing system (1)
1	• Greenland Ecosystem Monitoring program • Arctic-HYCOS • Fluxnet • PEEX (Pan-Eurasian EXperiment) • PROMICE automatic weather station network • Polish Polar Station Hornsund • Airborne observations of surface-atmosphere fluxes
2	
3	• Sodankylä Observatory
4	
5	
6	• Glacier Thickness Database (GlaThiDa) • GLISN, Danish seismological network • GNET - GPS networks • Norwegian National Seismic Network (NNSN) • Randolph Glacier Inventory (RGI) • World Glacier Monitoring Service-Fluctuations of Glaciers Database

4.1.5 Gaps in the sustainability of the observing system

This section describes the maturity in the sustainability of the addressed observing systems. The gap in the sustainability can be seen from the difference between the observed maturity level and the highest level provided. Scientific and expert support, funding support, site representativeness (for land based stations) are assessed for each observing system and classified on a scale from 1 to 6 (Table 10). Criteria are explained below as in the questionnaire A.

Scientific and expert support: The degree of scientific and technical expertise that underpins the measurement program.

1. None (No scientific or technical support is available)
2. Minimal scientific support required to sustain the program is available, sufficient to maintain the measurement program at present state, but not in case of major failure or breakdown of the observing system
3. Technical expertise is available to support operation of the observing system
4. As in (3) + at least two technical experts to secure the measurement program operation
5. *N/A*
6. As in (4) + research and development to ensure that the observing system is based on state of the art technology

Funding support: The long-term financial support that underpins the measurement program.

1. None (No dedicated funding support is evident for the measurement program)
2. Project based funding support available
3. As in (2) + expectation of follow on founding
4. As in (3) + not dependent upon a single investigator or funding line
5. Sustained infrastructure support available to finance continued operations for as far as can be envisaged given national and international funding vagaries
6. As in (5) + support for active research and development of instrumentation or applied analysis of the observations

Site representativeness (for terrestrial stations):

1. Unknown
2. *N/A*
3. The site only represents the immediate surrounding environment
4. The site is representative of a broader region around the immediate location
5. As in (4) + the site environment is likely to be unchanged for decades
6. As in (5) + the long-term site representativeness is guaranteed, e.g. due to protected area.

Table 10. Sustainability maturity matrix (in color scale: Maturity Level 1, Maturity level 2, Maturity level 3, Maturity level 4, Maturity level 5, Maturity level 6 (Missing).

Observing system	**Scientific and expert support**	**Funding support**	**Site representativeness (for land-based stations)**
Fluxnet (MPG, USFD, U Exeter)	1	2	3
PEEX (Pan-Eurasian EXperiment), UHEL	3	5	3
Sodankylä Observatory (FMI)	6	6	4
Airborne observations of surface-atmosphere fluxes (GFZ)	4	4	5

PROMICE Automatic weather station network (GEUS)	6	6	4
Fluctuations of Glaciers Database (FoG) (UPM)	5	6	3
Glacier Thickness Database (GlaThiDa) (UPM)	5	6	3
Randolph Glacier Inventory (RGI) (UPM)	5	6	3
Polish Polar Station Hornsund	4	5	3
Greenland Ice Sheet Monitoring Network (GLISN)	6	3	6
Norwegian National Seismic Network (NNSN)	6	6	5
Greenland GPS Network (GNET)	5	5	5
Arctic-HYCOS river discharge (SMHI)	5	5	5

4.1.6 Summary of the data usage

In this section, the usage of the data collected by the in situ observing systems is summarized. Fig. 47 shows that a significant part (8 of 24 classified) of the assessed observation systems are "focused" networks, with 6 each in the categories "distributed" and "operational" networks and 4 in the category "broad". Note that the lack of "commercial" or "resource-extraction" network may not reflect a real absence of such network; instead it is a manifestation of the selection of networks assessed. Table 11 shows the breakdown of the networks according to classification.

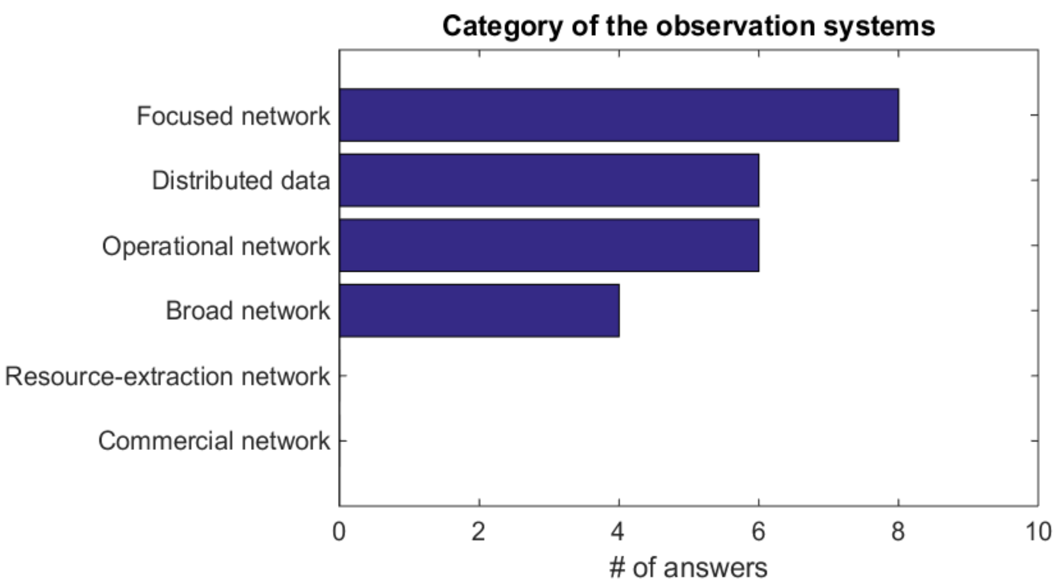

Figure 47. Categories of the addressed in situ observing systems. The categories are defined according to Eicken et al. (2013).

Table 11. List of in situ observing systems belonging to each category

Category	In situ observing system

Focused network (confined to specific themes or disciplines)	• FMI Sodankylä • PROMICE automatic weather station network • GLISN network Greenland • Greenland Climate Network (GC-Net) • Airborne observations of surface-atmosphere fluxes • Arctic-HYCOS • Norwegian National Seismic Network (NNSN) • Fluxnet
Operational network (feeding data into weather service and forecasting entities)	• FMI Sodankylä • PROMICE automatic weather station network • GLISN network Greenland • Greenland Climate Network (GC-Net) • Arctic-HYCOS • Svalbard Automated Weather and Snow Measuring System • Norwegian National Seismic Network (NNSN)
Distributed data (from many local networks)	• GLISN network Greenland • Arctic-HYCOS • World Glacier Monitoring Service-Fluctuations of Glaciers Database • Glacier Thickness Database (GlaThiDa) • Randolph Glacier Inventory (RGI) • Norwegian National Seismic Network (NNSN)
Broad network (it includes a broad range of interdisciplinary observations and projects)	• WMO Integrated Global Observing System (WIGOS) - Regional Basic Synoptic Network (RBSN) - Hornsund 01003 (Polish Polar Station) • Greenland Ecosystem Monitoring program • GNET - GPS networks • SIOS Airborne Infrastructure

Fig. 48 shows the distribution of application areas. In general climate is by far the largest application; the three largest groups relate to “climate research and monitoring”, which is the most common application, followed by “process oriented research”. The latter can be both related to climate model development and to development of “climate services” but also to “operational services”, for example development of weather forecast models.

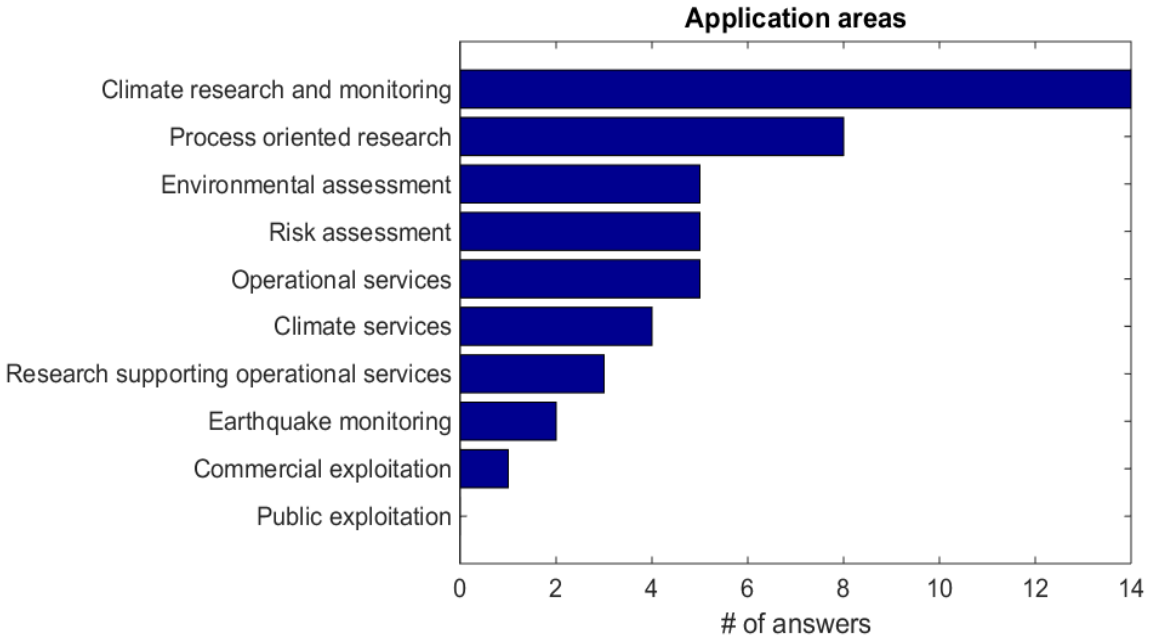

Figure 48. Application areas of the addressed in situ observing systems.

4.1.7 Gaps in the data management

This section describes the maturity in the data management of the observing systems. Data storage, data access, user feedback, updates to records, version control, and long term data preservation are assessed for each observing system and classified on a scale from 1 to 6 (Table 12). Criteria are explained below as in the questionnaire A.

Data storage:

1. Data are not stored in any institutional repository, but in a personal repository.
2. Data are stored in an institutional/departmental repository
3. Data are stored in distributed repositories (institutional and not)
4. Data are stored in a National repository according to legal constraints on their location
5. Data are stored in National data repositories without legal constraints on their location
6. Data are stored in International data repositories

Data access: Level of open distribution of data, documentation of data, and any software to process the data from raw measurement to geophysical variables needed by the users. The highest scores in this category can only be attained for data provided free of charge without restrictions on use and reuse.

1. Unknown
2. Data is available request to trusted users or through supervision by originator
3. Data is available on automated request through originator
4. Data and documentation are available on supervised request through originator
5. Data and documentation are available on automated request through originator

6. As (5) + source data, code and metadata available upon request or automated without any restrictions

User feedback: Level of established mechanisms to receive, analyse and ingest user feedback.
1. None
2. Ad hoc feedback (which may be acted upon)
3. Programmatic feedback (systematic collection of user feedback related to the measurements and dissemination of lessons learnt)
4. As in (3) + consideration of published analyses
5. Established feedback mechanism and international data quality assessment results are considered
6. As in (5) + Established feedback mechanism and international data quality assessment results are considered in continuous data provisions

Updates to record: Level of systems in place to update data records when new observations or insights become available.
1. None (No update is made to the measurement series or data products after initial release)
2. Irregularly following accrual of a number of new measurements scientific exchange and progress or new insights
3. *N/A*
4. Regularly updated with new observations and utilizing input from established feedback mechanism
5. Regularly operationally by stable data provider as dictated by availability of new input data or new innovations
6. As in (5) + initial version of measurement series or data products shared in near real time.

Version control: Level of measure taken to trace back the different versions of algorithms, software, format, input and ancillary data, and documentation used to generate the data record under consideration.
1. None
2. Versioning by data collector
3. N/A
4. Version control institutionalized and procedure documented
5. Fully established version control considering all aspects
6. As in (5) + all versions retained and accessible upon request

Long term data preservation: Level of Long Term Data Preservation according to ESA-guidelines (http://earth.esa.int/gscb/ltdp/).
1. None
2. Local archive retained by measurement collector
3. *N/A*
4. Each version archived at an institutional level on at least two media
5. Data, raw data and metadata is archived at a recognized data repository, national archive, or international repository.
6. As in (5) + all versions of measurement series, metadata, software etc. retained, indexed and accessible upon request.

Table 12. Data management matrix (in color scale: Maturity Level 1, Maturity level 2, Maturity level 3, Maturity level 4, Maturity level 5, Maturity level 6). Missing answers are marked in grey (Missing).

Observing system	Data storage	Data access	User feedback	Updates to record	Version control	Long term data preservation
Fluxnet	4	3	1	3	3	4
PEEX	2	2	2	2	2	4
Sodankylä Observatory	2	5	2	4	2	3
Airborne observations of surface-atmosphere fluxes	2	2	2		2	4
Fluctuations of Glaciers Database (FoG)	6	6	5	3	3	5
Glacier Thickness Database (GlaThiDa)	6	6	3	3	5	5
Randolph Glacier Inventory (RGI)	6	6	6	3	5	5
Polish Polar Station Hornsund	4	3	2	2	2	4
PROMICE Automatic weather station network	5	6	2	6	5	5
Greenland Ice Sheet Monitoring Network	6	6	3	3	3	6
Norwegian National Seismic Network	6	6	2	1	1	5
Greenland GPS Network	5	5	5	5	5	5
Arctic-HYCOS river discharge	5	5	1	4	4	4

4.2 In situ and airborne data collections

The data collections belonging to an observing system have generally different characteristics in terms of traceability, uncertainty, resolution. Most of these characteristics depend on the applied instrumentation. The data assessment is performed analyzing the data characteristics obtained through questionnaire B, and it consists of maturity matrices of the data collections, and an evaluation of key properties of the data with respect to the quantitative user-defined requirements given in Sect 3. In Sect. 4.2.1, the general information on the assessed data collections (such as observed variables, applied instrumentation, and temporal/spatial coverage) are summarized, while Sect. 4.2.2, 4.2.3, and 4.2.4 contain the assessments of the gaps in spatial-temporal resolution, uncertainty, and documentation, respectively.

The presented results concern the data collections described in Sect 2 and included in the project work plan. The assessment can however be expanded and integrated as continuation work after the end of INTAROS, following the needs and priorities defined by the user communities.

The keys info of each data collection will be integrated into the Data catalogues (Deliverable D2.9).

4.2.1 General information

The key information on the assessed data collections are summarized in Table 13. These include the assessor contact information, the measured variables and the instruments used, as well as the corresponding observing system and the administrating bodies for each of the assessed data collections.

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Table 13. Assessed terrestrial and cryospheric data collections

Name of data collection	Variables included in the data collection	Assessor of the data collection	Instrument	Observing System to which the data belong to	Administrating Bodies
PROMICE ice sheet ablation	ice sheet ablation	GEUS	Ørum & Jensen in GEUS assembly (NT1400 or NT1700)	PROMICE	GEUS
Eddy flux data (CO_2 and CH_4)	CO_2 and CH_4 fluxes	MPG, USFD, U Exeter	open path, LICOR LI-7500, enclosed path LICOR LI-7200, open path LICOR LI-7700 closed path LICOR LI-7000 closed path Closed path Los Gatos LGR-FGGA-24EP	Fluxnet (Ameriflux)	Fluxnet ORNL DAAC (Ameriflux DOE Office of Biological and Environmental Research (BER))
Data collection "Temperature profiles of the soil/peat layers at Russian Arctic stations"	Temperature profiles of the soil/peat layers, and soil/peat temperature profile down to the bed rock (bore hole)	Hanna K. Lappalainen (UHEL); Alexander Mahura (UHEL) (PEEX, UHEL)	autonomic loggers HOBO for measuring the temperature of permafrost	PEEX (Pan-Eurasian Experiment)	University of Helsinki (UHEL), Institute for Atmospheric and Earth System Research (INAR), & owners of the measurement stations
ERA-CLIM2 in situ SWE	SWE, snow depth, density	Anna Kontu (FMI)	manual: different types of snow tubes and snow depth probes, automated: snow pillow	FMI Sodankylä Observatory	Finnish Meteorological Institute (FMI)
Precipitation, snow depth, air temperature from AWS in Finland	precipitation, snow depth, air temperature (among others)	Anna Kontu (FMI)	precipitation: Vaisala VRG, snow depth: Campbell Scientific SR50, air temperature: PT100	FMI Sodankylä Observatory	Finnish Meteorological Institute (FMI)

Manual SYNOP observations	snow depth (among others)	Anna Kontu (FMI)	fixed depth probe	FMI Sodankylä Observatory	Finnish Meteorological Institute (FMI)
Snow scale SWE	SWE	Anna Kontu (FMI)	Sommer Messtechnik SSG1000	FMI Sodankylä Observatory	Finnish Meteorological Institute (FMI)
Soil frost stations	Soil temperature profile, soil dielectric constant profile, snow temperature profile	Anna Kontu (FMI)	soil: Decagon Devices 5TE Soil Moisture Sensor, snow: Campbell Scientific 107-L	FMI Sodankylä Observatory	Finnish Meteorological Institute (FMI)
AIRMETH_turbulent_fluxes_Polar5	CH4, CO2 , sensible and latent heat fluxes	Katrin Kohnert, Andrei Serafimovich, Torsten Sachs (GFZ)	Research aircraft Polar-5 of Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (AWI) equipped with among others: (Fast) Greenhouse Gas Analyzer (2012: RMT-200, Los Gatos Research Inc., 2013: FGGA 24 EP Los Gatos Research Inc.), Pyranometer (CMP22, Kipp and Zonen), Pyrgeometer (CGR 4, Kipp and Zonen), 5-hole probe	Airborne observations of surface-atmosphere fluxes	GFZ
Snow cover - Hornsund glaciers (USlaski)	snow depth	Mariusz Grabiec (USlaski)	GPR, other		University of Silesia (USlaski)
Front velocity of tidewater glaciers (USlaski)	Velocity	Małgorzata Błaszczyk (USlaski)	dGPS Leica		University of Silesia (USlaski)
Hornsund snow cover monitoring on tundra (IGPAN)	Snow depth and SWE on tundra	P. Głowacki (IGPAN)	Ablation stake readings, snow probing and snow pits	Polish Station - Hornsund	Institute of Geophysics, Polish Academy of Sciences (IGPAN)
FoG database: Glacier-wide surface mass balance (UPM)	Glacier-wide surface mass balance (winter, summer, annual)	Francisco Navarro and M.I. Corcuera (UPM)	Stake readings, snow probing and snow pits	Fluctuations of Glaciers Database (FoG)	World Glacier Monitoring Service (WGMS)

FoG database: Point surface mass balance	Point surface mass balance (winter, summer, annual)	Francisco Navarro and M.I. Corcuera (UPM)	Stake readings, snow probing and snow pits	Fluctuations of Glaciers Database (FoG)	World Glacier Monitoring Service (WGMS)
FoG database: Point snow density	Point snow density (winter, summer, annual)	Francisco Navarro and M.I. Corcuera (UPM)	Snow pits	Fluctuations of Glaciers Database (FoG)	World Glacier Monitoring Service (WGMS)
GlaThiDa: Glacier Ice Thickness	Ice thickness	Francisco Navarro and M.I. Corcuera (UPM)	Mostly Ground-penetrating radar (GPR)	Glacier Thickness Database (GlaThiDa)	World Glacier Monitoring Service (WGMS)
RGI: Glacier outlines	Glacier outline coordinates (Long, Lat)	F. Navarro and M.I. Corcuera (UPM)	Mostly satellite optical imagery	Randolph Glacier Inventory (RGI)	National Snow and Ice data Center (NSIDC)
GLISN	Seismic ground velocities	GLISN Steering Committee (www.glisn.info)	Broad band seismometers (primarily STS-2/CMG3TB sensors and 24bit digitizers primarily Q330/Centaur/REFTEK-130)	GLISN	GLISN Steering Committee
NNSN	Seismic ground velocities	UiB	Seismometers (SS1, STS2, Trillium120, CMG3ESP, CMG3T, S13, CMG6TD, CMG40T, HS10-1) and digitizers (DM24, Q330, SARA)	NNSN	NNSN board, UiB
3D surface displacement from GPS	ice mass change	DTU	GPS	GNET	Shfaqat Abbas Khan - DTU
AIRMETH_turbulent_fluxes_Polar5	Greenhouse gas and heat fluxes (CH4, CO2, latent and sensible heat)	A. Serafimovich, K. Kohnert, T. Sachs (GFZ)		Airborne observations of surface-atmosphere fluxes	

Front positions of tidewater glaciers in Hornsund (S Svalbard)	Front positions	M. Błaszczyk (USlaski)			
Earthquake catalogue	Source parameters of seismic events	P. Voss (GEUS), M. B. Sørensen (UiB)		Global earthquake monitoring	
Arctic-HYCOS GRDC archive	River discharge	David Gustafsson (SMHI)	River discharge is derived from water level (stage) measurements and stage-discharge relationships (so-called rating curves) derived and updated from irregular to regular discharge measurements. The instruments and rating curve parameters used for the ArcticHYCOS data are currently not specified in the GRDC Arctic-HYCOS documentation or metadata..	Arctic-HYCOS	Environment and Climate Change Canada (EC); Danish Meteorological Institute (DMI); Finnish Environmental Institute (FMI); Iceland Meteorological Office (IMO); Norwegian water Resources and Energy Directorate (NVE); State Hydrological Institute of Roshydromet (SHI); Swedish Meteorological and Hydrological Institute (SMHI); U.S. Geological Survey (USGS); Global Runoff Data centre (GRDC); World Meteorological Organization (WMO)

The Technology maturity readiness of the instruments used to generate the measured parameters of the assessed data collections (in Table 13) is provided in Table 14. Assessment criteria follow the ISO standard 16290 consisting of 9 different categories of Technology Readiness Levels (TRL), which in the report are adjusted on a scale from 1 to 6:

1. TRL1: Basic principles observed.
   TRL2: Technology concept formulated.
2. TRL3: Experimental proof of concept.
   TRL4: Component and/or breadboard functional verification in laboratory environment.
3. TRL5: Component and/or breadboard critical function verification in relevant environment.
4. TRL6: Model demonstrating the critical functions of the element in a relevant environment.
5. TRL7: Model demonstrating the element performance for the operational environment.
6. TRL8: Actual system completed and accepted for flight ("flight qualified").
   TRL9: Actual system "flight proven" through successful mission operations.

Table 14. Technology Readiness Level (in color scale: TRL1-2, TRL3-4, TRL5, TRL6, TRL7, TRL8-9) of the instruments applied to measure/derive the assessed variables.

Data collection	Instrument	Measured/derived variable
eddy flux data (CO_2 and CH_4) (USF, MPG, U Exeter)	open path, LICOR LI-7500 closed path LICOR LI-7000 open path LICOR LI-7700 closed path Closed path Los Gatos LGR-FGGA-24EP (TRL6)	CO_2 and H_2O fluxes, CO_2 and H_2O concentration, air Temperature CO_2 and H_2O fluxes, CO_2 and H_2O concentration, cell temperature and pressure CH_4 fluxes, CH_4 concentration, air temperature CO_2 CH_4 and H_2O fluxes, CO_2 CH_4 and H_2O concentration, cell temperature and pressure
Data collection “Temperature profiles of the soil/peat layers at Russian Arctic stations” (PEEX, UHEL)	autonomic loggers HOBO for measuring the temperature of permafrost with a given frequency (4 times per day) at main depths (0, 2, 3, 5 and 10 m) (TRL2)	soil temperature measurements at different peat layers (vertical profile)
ERA-CLIM2 in situ SWE (FMI)	different types of snow tubes, snow depth sticks, snow pillows (TRL9)	Measured: SWE, depth Derived: density
Precipitation, snow depth, air temperature from AWS in Finland (FMI)	precipitation: Vaisala VRG, snow depth: Campbell Scientific SR50, air temperature: PT100 (TRL9)	Measured: Precipitation, air temperature (among others) Derived: snow depth
Manual SYNOP observations (FMI)	fixed depth probe (TRL9)	Measured: Snow depth

Snow scale SWE (FMI)	Sommer Messtechnik SSG1000 (TRL9)	Measured: SWE
Soil frost station (FMI)	soil: Decagon Devices 5TE Soil Moisture Sensor, snow: Campbell Scientific 107-L (TRL9)	Measured: Soil temperature and dielectric constant profiles, snow temperature profile
AIRMETH_turbulent _fluxes_Polar5 (GFZ)	Los Gatos Research FGGA-24EP (RMT-200 in 2012) Rosemount 5-holes probe open wire Pt100 in an unheated Rosemount housing Entire instrumentation on Polar5 (TRL9)	Measured variables: CH4, CO2, and water vapor concentration Wind vector from pressure differences Air temperature Derived variables: CH_4, CO_2, and H_2O fluxes
Snow cover - Hornsund glaciers (USlaski)	CUII/ProEx radar system, 800 MHz shielded antenna (TRL 5)	snow depth
Front velocity of tidewater glaciers (USlaski)	Leica 1230 (TRL9)	Stakes positions and displacements, glacier velocity
Hornsund snow cover monitoring on tundra (IGPAN)	Manual measurements from ablation stakes and snow probing (TRL9), time lapse cameras (TRL9)	Snow depth, SWE
FoG database: Glacier-wide surface mass balance (UPM)	Stake readings, snow probing and snow pits (TRL9)	Glacier-wide surface mass balance (winter, summer, annual)
FoG database: Point surface mass balance (UPM)	Stake readings, snow probing and snow pits (TRL9)	Point surface mass balance (winter, summer, annual)
FoG database: Point snow density (UPM)	Snow pits (TRL9)	Point snow density (winter, summer, annual)
GlaThiDa: Glacier Ice Thickness (UPM)	Mostly Ground-penetrating radar (GPR) (TRL9)	Ice thickness
RGI: Glacier outlines (UPM)	Satellite optical imagery (TRL9)	Glacier outline coordinates (Long, Lat)
GLISN (GEUS)	Broad band seismometers (primarily STS-2/CMG3TB sensors and 24bit digitizers primarily Q330/Centaur/REFTEK-130) (TRL9)	Seismic ground velocity
NNSN (UiB)	Seismometers (SS1, STS2, Trillium120, CMG3ESP, CMG3T, S13, CMG6TD, CMG40T, HS10-1) and digitizers (DM24, Q330, SARA) (TRL9)	Seismic ground velocity

3D surface displacement from GPS (DTU)	GPS (TRL9)	3D bedrock displacement
AIRMETH_turbulent_fluxes_Polar5	Los Gatos Research FGGA-24EP (RMT-200 in 2012) Rosemount 5-holes probe open wire Pt100 in an unheated Rosemount housing Entire instrumentation on Polar5 (TRL9)	Measured variables: CH4, CO2, and water vapor concentration Wind vector from pressure differences Air temperature Derived variables: CH4, CO2, and H2O fluxes
Earthquake catalogue	(TRL9)	Source parameters of seismic events
Mass balance of Hansbreen glacier at Svalbard(USlaski)	Stake readings, snow probing and snow pits (TRL9)	mass balance, ablation stakes - glacier movement
Arctic-HYCOS GRDC archive (SMHI)	River discharge is derived from water level (stage) measurements and stage-discharge relationships derived and updated from irregular to regular discharge measurements. Instruments used for the Arctic-HYCOS data collection is unknown from the GRDC metadata. TRL8-9	Water level (measured)/River discharge (derived)

Most of the instruments applied have TRL 8-9. This is the case also for the very simple manual tools such as snow stakes, thermistor probes, or snow samplers applied to collect snow measurements. Despite their simplicity and many shortcomings, they have been applied for many decades and robust assessments on their accuracy and performance have been published.

4.2.2 Gaps in spatial-temporal coverage and resolution

This section analyses the spatio-temporal gaps in data collections. The requirements are set for each data collection in Sect. 3 with criteria level **goal**, **breakthrough**, and **threshold** when relevant. In Table 15, spatial vertical and horizontal coverage (i.e. measurement locations) of each data collection is compared with the corresponding requirements. In Table 16, spatial vertical and horizontal resolution (i.e. density of measurements) of each data collection is compared with the corresponding requirements. In Tables 17 and 18 the data temporal coverage (i.e. measurement time period) and temporal resolution (i.e. instrument/collection time resolution) and presented and compared with the corresponding requirements. Table 19 presents the data collections timeliness (i.e. how fast the data become available after collection).

Table 15. Spatial coverage

Data collection	Horizontal coverage of observations	Vertical coverage of observations	Required horizontal coverage	Required vertical coverage	Comparison: observed vs required
Eddy flux data (CO_2 and CH_4) (USF, MPG, U Exeter)	single location measurements	usually one height above ground level	network needs to be extended for more representative coverage, particularly for CH4, and winter	one single height is the standard for EC systems	The spatial network coverage should be extended to close existing gaps described in section 2.6, and 2.7. Gaps do not follow strict resolution metrics, but are rather dependent on the variability in ecosystem and climate conditions across the Arctic, and how well these are represented in current site locations. The vertical coverage is not compromised.
Data collection "Temperature profiles of the soil/peat layers at Russian Arctic stations" (PEEX, UHEL)	measurements are performed at exact geographical points/ locations of the sites (at single locations)	vertical profile of soil temperature in peat layers (0, 2, 3, 5, 10 meters)	more dense network of stations would be desirable along the longitudinal belt of the Russian Arctic	basic standard measurements for selected parameters	more dense network of stations would be desirable along the longitudinal belt of the Russian Arctic; although vertical coverage follows the standard measurements, but additional levels of measurements would be desirable
ERA-CLIM2 in situ SWE (FMI)	Canada, Finland, Russia	bulk measurement	Global	bulk measurement, not relevant	The northernmost parts are sparsely covered.
Precipitation, snow depth, air temperature from AWS in Finland (FMI)	Sodankylä (network covers whole Finland)	0-2 m	Finland	point/bulk measurements, not relevant	Requirements filled.

Manual SYNOP observations (FMI)	Sodankylä	bulk measurement		bulk measurement, not relevant	Historical (>100 years) time series at one location. Some other long snow depth time series exist.
Snow scale SWE (FMI)	One point measurement	bulk measurement	Wider network of automated measurements required	bulk measurement, not relevant	Only one point measurement, not enough for e.g. satellite cal/val purposes.
Soil frost stations (FMI)	18 stations in Sodankylä and Saariselkä regions in Northern Finland	soil at 5 depths (5 to 80 cm), snow at 13 heights (0 to 120 cm)	Typical soil types.	-1 m to 1 m	Requirements filled. A few new stations installed yearly to new locations.
AIRMETH_turbulent_fluxes_Polar5 (GFZ)	AIRMETH_turbulent_fluxes_MackenzieCanada| AIRMETH_turbulent_fluxes_NorthSlopeAlaska|	Single level measurement	One study area in each mayor arctic zone (Alaska, Canada, Russia, Europe)	Single level measurement	Horizontal coverage: lacking reliable data for Russia and Europe Vertical coverage requirement is met already
Snow cover - Hornsund glaciers (USlaski)	Hansbreen| glacier area	depth: 0-6 m below surface level	Hornsund glaciers	depth: 0-6 m below surface level	Horizontal coverage needs to be expanded to more glaciers in Hornsund area. Vertical coverage - adequate
Front velocity of tidewater glaciers (USlaski)	Hansbreen Z| POINT (77.02 15.64) Storbreen R| POINT (77.10 16.36) Hornbreen T| POINT (77.07 16.65) Hornbreen U| POINT (77.06 16.70)	0 m (surface level)	Hornsund glaciers	0 m (surface level)	Horizontal coverage needs to be expanded to more glaciers in Hornsund area. Vertical coverage - adequate
Hornsund snow cover monitoring on	Snow cover at meteorological station (depth and SWE since 1982) and spatial	ground level	Unglaciated catchment (1km^2)	Bulk measurement, not relevant	The variety of snow cover is high on tundra

tundra (IGPAN)	distribution at Fuglebekken ctchment (since 2013)				
FoG database: Glacier-wide surface mass balance (UPM)	A variable number of glaciers in each of the GTN-G Glacier Regions in the Arctic: Alaska, Canadian Arctic North, Canadian Arctic South, Franz Josef, Greenland Periphery, Iceland, Svalbard & Jan Mayen, Mackencie, Novaya Zemlya, Severnaya Zemlya	The glacier altitude range, which is typically of several hundred m up to a few km within 0 and 8000 m a.s.l.	A sufficient sample of glaciers in each of the GTN-G Glacier Regions in the Arctic. The required number should increase with the number of glaciers in the region and/or its total glacierized area	The glacier altitude range, which is typically of several hundred m up to a few km within 0 and 8000 m a.s.l.	The horizontal and vertical coverages at each individual glacier are usually OK, except at the high-slope areas of the glaciers or the highly crevassed frontal areas of the marine-terminating glaciers. However, as concerns the geographical coverage of the various Arctic regions, of a total of about 61,400 individual glaciers in the Arctic region, covering a total area of about 420,000 km2, there are SMB series for 106 of them, but only 32 are maintained at present. Moreover, the geographical distribution is quite irregular. Iceland is, by far, the best covered area, while the Russian Arctic is the worst covered area (with null coverage at present). Peripheral Greenland is poorly covered, and the Canadian Arctic is also under-represented, especially at present and taking into account its large glacierized area. The rest of regions are fairly well covered.
FoG database: Point surface mass balance (UPM)	A variable number of glaciers in each of the GTN-G Glacier Regions in the Arctic: Alaska, Canadian Arctic North, Canadian Arctic South, Franz Josef, Greenland Periphery, Iceland, Svalbard & Jan Mayen, Mackencie, Novaya Zemlya, Severnaya Zemlya	A set of single level measurement at variable height within the glacier altitude range, which is typically of several hundred m to a few km, within 0 and 8000 m a.s.l.	A sufficient sample of glaciers in each of the GTN-G Glacier Regions in the Arctic. The required number should increase with the number of glaciers in the region and/or its total glacierized area	A set of single level measurement at variable height within the glacier altitude range, which is typically of several hundred m to a few km, within 0 and 8000 m a.s.l.	Same comment as for glacier-wide surface mass balance above.

FoG database: Point snow density (UPM)	A variable number of glaciers in each of the GTN-G Glacier Regions in the Arctic: Alaska, Canadian Arctic North, Canadian Arctic South, Franz Josef, Greenland Periphery, Iceland, Svalbard & Jan Mayen, Mackencie, Novaya Zemlya, Severnaya Zemlya	Result of vertical integration along the snow layer thickness (typically < 3m), measured at points at variable height within the glacier altitude range, which is typically of several hundred m to a few km, within 0 and 8000 m a.s.l.	A sufficient sample of glaciers in each of the GTN-G Glacier Regions in the Arctic. The required number should increase with the number of glaciers in the region and/or its total glacierized area	Result of vertical integration along the snow layer thickness (typically < 3m), measured at points at variable height within the glacier altitude range, which is typically of several hundred m to a few km, within 0 and 8000 m a.s.l	Same comment as for glacier-wide surface mass balance above, with the particularity that the density data stored in the WGMS databases is much more limited than the surface mass balance data available.
GlaThiDa: Glacier Ice Thickness (UPM)	A variable number of glaciers in each of the GTN-G Glacier Regions in the Arctic: Alaska, Canadian Arctic North, Canadian Arctic South, Franz Josef, Greenland Periphery, Iceland, Svalbard & Jan Mayen, Mackencie, Novaya Zemlya, Severnaya Zemlya	The glacier altitude range, which is typically of several hundred m up to a few km within 0 and 8000 m a.s.l.	A sufficient sample of glaciers in each of the GTN-G Glacier Regions in the Arctic. The required number should increase with the number of glaciers in the region and/or its total glacierized area	The glacier altitude range, which is typically of several hundred m up to a few km within 0 and 8000 m a.s.l.	Of a total of about 61,400 individual glaciers in the Arctic region, covering a total area of about 420,000 km2, there is ice-thickness data for about 1050 glaciers. However, only for a small fraction of these glaciers the ice-thickness data coverage is sufficient to provide a good ice volume estimate. Many of the glaciers have been covered by airborne ground-penetrating radar campaigns campaigns that provide data only along the glacier centerline. Moreover, concerning regional distribution the spatial coverage is very irregular. The regions with far more ice-thickness data are those that have been covered by airborne ground-penetrating radar campaigns (mostly by the IceBridge Operation). The Canadian Arctic, Peripheral Greenland and Svalbard & Jan Mayen are the best covered regions (about 1000 records in total), while the rest of regions have in total just a few records (about 50).
RGI: Glacier outlines (UPM)	All glaciers in each of the GTN-G Glacier Regions in the Arctic: Alaska, Canadian Arctic North, Canadian Arctic South, Franz	The glacier altitude range, which is typically of several hundred m up to a few km within 0 and 8000 m a.s.l.	All glaciers in each of the GTN-G Glacier Regions in the Arctic: Alaska, Canadian Arctic North, Canadian Arctic	The glacier altitude range, which is typically of several hundred m up to a few km within 0 and 8000 m a.s.l.	The coverage is total (pan-Arctic). There are available glacier outlines for each of the about 61,400 individual glaciers in the Arctic region. This has been possible thanks to the remote sensing satellite tools available nowadays.

	Josef, Greenland Periphery, Iceland, Svalbard & Jan Mayen, Mackencie, Novaya Zemlya, Severnaya Zemlya		South, Franz Josef, Greenland Periphery, Iceland, Svalbard & Jan Mayen, Mackencie, Novaya Zemlya, Severnaya Zemlya		
GLISN (GEUS)	Two sensors in North and East direction	One sensor	n/a	n/a	If only vertical sensor is available, the determination of seismic wave velocity and azimuth is not possible and of S-wave travel time very uncertain.
NNSN (UiB)	Two sensors in North and East direction	One sensor	n/a	n/a	If only vertical sensor is available, the determination of seismic wave velocity and azimuth is not possible and of S-wave travel time very uncertain.
3D surface displacement from GPS (DTU)	entire coastal Greenland	n/a	entire coastal Greenland	n/a	few more sites in west Greenland are recommended
AIRMETH_turbulent_fluxes_Polar5	AIRMETH_turbulent_fluxes_MackenzieCanada| AIRMETH_turbulent_fluxes_NorthSlopeAlaska	Single level measurement	Pan-Arctic (covering one region per geographical)	Single level measurement	Vertical coverage requirement is already met. The horizontal coverage should be increased to a region in the European and Russian Arctic
Front positions of tidewater glaciers in Hornsund (S Svalbard)	Hornsund catchment area	Single level measurement	Hornsund glaciers	Single level measurement	Horizontal and vertical coverage - adequate
Earthquake catalogue	Seismic events are detected across the arctic region	Events are detected in the continental and oceanic crust	Pan-Arctic	Continental and oceanic crust	Earthquakes below magnitude 4.5 are likely not be detected in large parts of the Arctic region (see Fig. 2.2.7 in D2.7).
Arctic-HYCOS GRDC archive	427 stations of which 80 can be used for flow-to-ocean	n/a	75% of the flow-to-ocean and 75% of the spatial variability in	n/a	The spatial coverage and the representation of the total flow to ocean is around 60% which might be good enough, but still somewhat lower than the tentative requirement (75%).

	estimation. The drainage basins of the stations cover 58% of the spatial domain and represent 56 % of the total estimated flow-to-ocean (63% and 61%, respectively if Greenland is excluded.		the Arctic hydrological regimes		

Table 16. Spatial resolution

Data collection	Horizontal resolution of observations	Vertical resolution of observations	Required horizontal resolution	Required vertical resolution	Comparison: observed vs required
Eddy flux data (CO_2 and CH_4) (USFD, MPG, U Exeter)	single location measurements	usually one height above ground level	network needs to be extended for more representative coverage, particularly for CH4, and winter	one single height is the standard for EC systems	As mentioned in Table 11 above, gaps do not follow strict resolution metrics, but are rather dependent on the variability in ecosystem and climate conditions across the Arctic, and how well these are represented in current site locations. The vertical coverage is not compromised.
Data collection "Temperature profiles of the soil/peat layers at Russian Arctic stations" (PEEX, UHEL)	measurements are performed at exact geographical points/ locations of the sites (at single locations)	basic standard measurements of the vertical profile (0, 2, 3, 5, 10 meters)	basic standard measurements at fixed locations	basic standard measurements for selected parameter	although vertical coverage is following the standard measurements, but might be additional levels of measurements would be desirable
ERA-CLIM2 in situ SWE (FMI)	Snow courses cover distances of 0.5-4 km, distance between measurements on a course is 20-500 m. Distance between separate courses is random.	bulk measurement	Regular grid	bulk measurement, not relevant	The northernmost parts are sparsely covered. Grid is not regular, but areas around 50 N are well covered. The number of measurement locations is declining.
Precipitation, snow depth, air temperature from AWS in Finland (FMI)	Point measurement. Network covers whole Finland.	Point/bulk measurements.	Point measurement. Network covers whole Finland.	Point/bulk measurements, not relevant.	Requirements filled.

Manual SYNOP observations (FMI)	Point measurement.	Bulk measurement.		Bulk measurement, not relevant.	Historical (>100 years) time series at one location. Some other long snow depth time series exist.
Snow scale SWE (FMI)	Point measurement.	Bulk measurement.	Finland/Global	Bulk measurement, not relevant.	Wider network of automated measurements required
Soil frost stations (FMI)	18 stations in Sodankylä and Saariselkä regions in Northern Finland	soil at 5 depths (5 to 80 cm), snow at 13 heights (0 to 120 cm)	Typical soil types.	-1 m to 1 m	Requirements filled. A few new stations installed yearly to new locations.
AIRMETH_turbulent_fluxes_Polar5 (GFZ)	100 m	-	100 m	-	The horizontal resolution is already met.
Snow cover - Hornsund glaciers (USlaski)	n/a	n/a	140 m 320 m 500 m	n/a	Technical and field conditions of measurements are not able to ensure results in regular grid. Snow depth resolution along profiles is higher than required however distance between profiles may be poor
Front velocity of tidewater glaciers (USlaski)	n/a	n/a	n/a	n/a	
Hornsund snow cover monitoring on tundra (IGPAN)	23 ablation stakes network	usually one height above ground level	network could be extended for more representative coverage along Hornsundfjord	one location (average depth of three stakes) is the WMO standard	dependent on the topographical variability in ecosystem and climate conditions
FoG database: Glacier-wide surface mass balance (UPM)	n/a	n/a	n/a	n/a	This does not apply to a variable, like surface mass balance, that is integrated over a certain area (the glacier basin).
FoG database: Point surface mass balance (UPM)	n/a	n/a	n/a	n/a	This does not apply to a variable, like point surface mass balance, that is representative of a certain area of undefined extent.

FoG database: Point snow density (UPM)	n/a	n/a	n/a	n/a	This does not apply to a variable, like snow density, that is representative of a certain area of undefined extent.
GlaThiDa: Glacier Ice Thickness (UPM)	Typically 3-30 m (for ice thickness determined using migration in the radar data processing).	Typically 3-30 m. The horizontal resolution depends on the frequency of the radar used	20-30 m	5 m	The horizontal and vertical resolutions provided by the currently-available radar systems is generally sufficient for the most common applications (though radar frequency should be chosen accordingly)
RGI: Glacier outlines (UPM)	Depending on region. Typically 5-15 m, but can be up to 60 m.	n/a	5-10 m	n/a	The currently-available satellite remote sensing tools are generally fit the resolution envisaged in most applications.
GLISN (GEUS)	n/a	n/a	n/a	n/a	This does not apply to seismometers
NNSN (UiB)	n/a	n/a	n/a	n/a	This does not apply to seismometers
3D surface displacement from GPS (DTU)	point measurements	n/a	n/a	n/a	n/a
AIRMETH_turbulent_fluxes_Polar5	100 m	-	100 m	-	Requirements are already met
Front positions of tidewater glaciers in Hornsund (Svalbard)	30-200m	n/a	10 m 50 m 100 m	n/a	Horizontal resolution meets the threshold level requirements
Earthquake catalogue	n/a	n/a	n/a	n/a	The information on the earthquakes in the catalogue is mainly provided for a point location.
Arctic-HYCOS GRDC archive	Width of the river sections represented by the measurements	Depth of the river sections represented by the measurements	Width of the river sections represented by the measurements	Depth of the river sections represented by the measurements	Requirement met.

Table 17. Temporal coverage

Data collection	Temporal coverage of observations	Required temporal coverage	Comparison: observed vs required
Eddy flux data (CO_2 and CH_4) (USF, MPG, U Exeter)	heterogeneous, between a few months and 24 years, and between continuous and summertime-only	at least 10 continuous data years. Year-round observations.	Only very few sites actually reach the goal of 10 consecutive data years, so for most of the network, sustained funding is essential to actually reach this threshold, and improve the usefulness of observations for climate change research. Again, only very few sites can offer continuous year-round observations, and capture the full annual budget of carbon exchange. This is a crucial gap, since wintertime processes have been shown to be important.
Data collection "Temperature profiles of the soil/peat layers at Russian Arctic stations" (PEEX, UHEL)	earliest start of time-series (among 11 stations) is from 1930 at Igarka GeoCryLab	continuation of observations (longer time-series) is needed, especially for climate studies	at 4 measurement stations (Seida Vorkuta, Kashin, Belyy, Heiss Island) the duration of measurements (since 2007, 2008, 2009, 2010) is relatively short for climate and ecosystem related studies (more measurements are needed)
ERA-CLIM2 in situ SWE (FMI)	1935-2017. Most measurements from 1965-2000.	Typically more than 30 years for climate studies	Requirement fulfilled
snow depth from AWS in Finland (FMI)	start: 2006.10.24	Typically more than 30 years for climate studies	Manual observations were replaced by automatic observations at AWS. Although the record of automatic data is only about 10y long, together with the manual observation it forms a very long record (about 1 century).
Manual SYNOP observations (FMI)	start: 1911.01.01 end: 2008.02.04	Typically more than 30 years for climate studies	Requirement fulfilled
Snow scale SWE (FMI)	start: 2015.11.10	Typically more than 30 years for climate studies	Sustained automated snow scale measurements not available for extended periods. Dataset can be extended with bi-monthly manual data
Soil frost stations (FMI)	3 stations in 2010, 7 in 2011, 2 in 2012, 4 in 2014, 2 in 2016	Typically more than 30 years for climate studies	Still growing network of soil stations supporting satellite CAL/VAL (eg. SMOS, SMAP) operations.
AIRMETH_turbulent_fluxes_Polar5 (GFZ)	2012/06-07 and 2013/07 and 2016/08-09	20 years with flights at least every second year (including spring/autumn campaigns)	Aircraft campaigns should continue at least until 2032. Measurements during the shoulder seasons are still missing.

Snow cover - Hornsund glaciers (USlaski)	2008-2017	2008-2017	Lack of data from 2009-2010, 2012
Front velocity of tidewater glaciers (USlaski)	2013-2015		Stakes positions measured only once per year. Need of continuous measurements.
Hornsund snow cover monitoring on tundra (IGPAN)	since 1982 at meteo site and since 2013 in Fuglebekken catchment	long-term	Spatial distribution measured once a week, could be measured more frequently (at station snow depth is measured daily)
FoG database: Glacier-wide surface mass balance (UPM)	Glacier-dependent. Typically within 5-50 years.	Minimum 10-20 years	The temporal coverage provided by the available data is OK regarding frequency of the mass balance observations (usually annual). However, time series of 10-20 yr length, required for climate-related studies, are rarely available in the Arctic region because of logistic difficulties and long-term sustainability of such long time series (e.g. due to limited duration of funding), unless the monitored glaciers are located close to Arctic permanent stations. A strong effort should be done to guarantee the continuity of the surface mass balance series.
FoG database: Point surface mass balance (UPM)	Glacier-dependent. Typically within 5-50 years.	Minimum 10-20 years	Same comment as above for glacier-wide surface mass balance.
FoG database: Point snow density (UPM)	Glacier-dependent. Typically within 5-50 years.	Minimum 10-20 years	Same comment as above for glacier-wide surface mass balance, with the particularity that snow density measurements are by far less abundant than surface mass balance observations.
GlaThiDa: Glacier Ice Thickness (UPM)	Usually a single set of GPR measurement for each glacier	Good single measurement is sufficient	Having available a single set of good ice-thickness measurements is sufficient, since ice thickness (and glacier volume) changes can then be easily (and cheaply) monitored through surface elevation changes, which can be done using satellite remotes sensing tools.
RGI: Glacier outlines (UPM)	A single set of glacier outlines available for most glaciers	Measurements repeated every 5-10 years (though ideally every year)	So far there is available a single set of outlines for each of the about 61,000 individual glaciers in the Arctic. It would be convenient to repeat such kind of measurements every ca. 5-10 years. This should be possible with the currently-available satellite remotes sensing tools.
GLISN (GEUS)	Since 2009	Year-round monitoring	Since initiation of GLISN most sites have been in operation year-round, gaps are mainly due to instrument failure.
NNSN (UiB)	Since 1905	Year-round monitoring	Sites are generally in continuous operation. Data gaps are mainly due to failure of instruments or communication.

3D surface displacement from GPS (DTU)	since 1995	1y	Fairly long time series since 2007
AIRMETH_turbulent_fluxes_Polar5	2012/06-07 2013/07 2016/08-09	15 years with flights at least every second year (including spring/autumn campaigns)	Alaska, Canada and Russia campaigns started in 2012 with some repetitions since, but repetition of Russia campaigns is still limited
Front positions of tidewater glaciers in Hornsund (S Svalbard)	1899-2010	Minimum once per year since medium resolution satellite images availability (ca. 1990's)	Front position detected in 1899–1936–1960/1961–1976–1990–2001–2005–2010
Earthquake catalogue	Covers the 50-year period 1965 – 2014	For natural hazards, 50 yrs is often the minimum requirement.	The detection of smaller size earthquakes has increased during the 50 years period.
Arctic-HYCOS GRDC archive	Average time series length about 50 years and maximum more than 100 years	More than 30 years	Requirement met.

Table 18. Temporal resolution

Data collection	Temporal resolution of observations	Required temporal resolution	Comparison: observed vs required
Eddy flux data (CO_2 and CH_4) (MPG, USFD, U Exeter)	Usually, fluxes are recorded and reported in 30-minute intervals	30-minute time steps are the established setup for EC measurements. For case studies focusing on CH_4, higher resolution fluxes (e.g. 1-minute) based on wavelet methods would be desirable.	The network provides the required temporal resolution to capture carbon fluxes, and monitor their variability over time for extended observation periods. Only for case studies and basic research, new methods that offer higher temporal resolution may be beneficial. This, however, can be achieved with the existing raw data.
Data collection "Temperature profiles of the soil/peat layers at Russian Arctic stations" (PEEX, UHEL)	measurements are performed at standard terms/ intervals (4 times per day, every 6 hours)	a shorter interval (3 hours) between measurements would be more desirable	a shorter interval between measurements would be more desirable

ERA-CLIM2 in situ SWE (FMI)	Typically one measurement per month per course.	Weekly or even daily data.	Frequency could be increased.
Precipitation, snow depth, air temperature from AWS in Finland (FMI)	10 min	10 min	Requirements filled.
Manual SYNOP observations (FMI)	1 day	1 day	Historical manual observations.
Snow scale SWE (FMI)	1 min	1 hour	Requirements filled.
Soil frost stations (FMI)	10 min	10 min	Requirements filled.
AIRMETH_turbulent_fluxes_Polar5 (GFZ)	2012, 2013, 2016	biannual	Requirement almost met
Snow cover - Hornsund glaciers (USlaski)	1 year	1 d 1 m 1 y	Temporal resolution meets the threshold level requirements
Front velocity of tidewater glaciers (USlaski)	ca. monthly	1 d 1 m 1 y	Temporal resolution meets the breakthrough level requirements for Hansbreen and threshold level for Storbreen and Hornbreen
Hornsund snow cover monitoring on tundra (IGPAN)	daily / weekly (spatial)	1 d 1 m 1 y	Temporal resolution meets the threshold level requirements
FoG database: Glacier-wide surface mass balance (UPM)	1 year (annual balance) 3 months (summer balance) 9 months (winter balance)	1 year (annual balance) 3 months (summer balance) 9 months (winter balance)	The analysed variables are either annual or seasonal. The samples should be taken during a period of about a week at the beginning and end of the melting season, and this requisite is often met.
FoG database: Point surface mass balance (UPM)	1 year (annual balance), 3 months (summer balance), 9 months (winter balance)	1 year (annual balance) 3 months (summer balance), 9 months (winter balance)	Same comment as above for glacier-wide surface mass balance.
FoG database: Point snow density (UPM)	1 year (annual balance), 3 months (summer balance) 9 months (winter balance)	1 year (annual balance) 3 months (summer balance) 9 months (winter balance)	Same comment as above for glacier-wide surface mass balance

GlaThiDa: Glacier Ice Thickness (UPM)	Typically 1-5 days	< 1 year	The radar campaigns are usually performed during a few days (if ground-based) or a few hours (if airborne), which is sufficient. Sometimes data from various subsequent years have to be combined, and this is OK as far as corrections for surface elevation changes during that period are taken into account.
RGI: Glacier outlines (UPM)	For each glacier, outlines often correspond to a single satellite image, but often data form various images, sometimes several weeks apart, are combined.	< 1 year	The required temporal resolution is most often achieved. The optical satellite images pose some problems (due to cloud coverage), but combination of images weeks to months apart is usually not problematic.
GLISN (GEUS)	Continuous with a sampling frequency of 20 or 100 Hz	For local seismicity 100Hz, for distant seismicity and local earth structure 20Hz and for surface wave recordings 1Hz	Requirements filled
NNSN (UiB)	Continuous with a sampling frequency of 100 Hz	For local seismicity 100Hz, for distant seismicity and local earth structure 20Hz and for surface wave recordings 1Hz	Requirements filled
3D surface displacement from GPS (DTU)	30 s interval	30 s interval	Requirements filled
Front positions of tidewater glaciers in Hornsund (S Svalbard)	variable, 1 to 37 years	1 d 1 m 1 y	Temporal resolution is equal or below the threshold level requirements. [M1] Temporal resolution increases after 2000.
Earthquake catalogue	n/a	n/a	The occurrence of new earthquakes cannot be controlled.
Arctic-HYCOS GRDC archive	Daily and Monthly data	Monthly	Requirement met.

Table 19. Timeliness

Data collection	Timeliness of observations	Required timeliness	Comparison: observed vs required

Eddy flux data (CO2 and CH4) (MPG, USFD, U Exeter)	Very heterogeneous. Data provision ranges between backlogs of a few months to several years.	For a representation of actual processes, a near real-time data provision would be necessary. To allow analyses of recent processes/anomalies within the 'public attention span', a provision within ~3 months would be required.	As a common practice, EC research groups often process data in annual batches. In some cases, these final datasets will then be directly uploaded to databases, i.e. the backlog is <= 1 year. For many of the sites in the network, however, data uploads to the databases is rather episodic. This is routed in the fact that few groups have sustained funding to support this time-intensive data resource management. It would be ideal if support could be provided to collect flux data in near real-time within a common database. This would facilitate the generation of synthesis products within the same season, or at least calendar year, which could be used to inform the public while attention may be still high.
Data collection "Temperature profiles of the soil/peat layers at Russian Arctic stations" (PEEX, UHEL)	all observations are available under request	data collections need to be available within a month period of time for the climate and ecosystem research community and other users;	The data are not publicly available, the requirements are not fulfilled.
ERA-CLIM2 in situ SWE (FMI)	Release of an updated dataset is not planned in near-future	n/a	Compilation of datasets from various sources.
Snow depth from AWS in Finland (FMI)	1 day (1 year for complementary stations requiring manual quality control; more often if needed)	1 day-1 min	Requirements filled
Manual SYNOP observations (FMI)	n/a	n/a	Historical data, not updated..
Snow scale SWE (FMI)	1 year (requires manual quality control), more often if needed	1 day	If quality control were automated, timeliness would increase significantly.
Soil frost stations (FMI)	1 year (requires manual quality control), more often if needed	1 day-1 year	If quality control were automated, timeliness would increase significantly. Some stations are not connected to network, data must be downloaded to USB stick and uploaded to distribution server manually.
AIRMETH_turbulent_fluxes_Polar5 (GFZ)	Data are accessible after an unknown period	Threshold: 6 months after the campaign	The timeliness has to be increased.

Snow cover - Hornsund glaciers (USlaski)	Data are accessible after an unknown period	7 d 1 m 1 y	Data accessibility doesn't meet requirements
Front velocity of tidewater glaciers (USlaski)	Data are accessible after an unknown period	7 d 1 m 1 y	Data accessibility doesn't meet requirements
Hornsund snow cover monitoring on tundra (IGPAN)	Data are accessible after a month or at any time on demand	7 d	Data accessibility doesn't meet requirements
FoG database: Glacier-wide surface mass balance (UPM)	Data are accessible some years after acquisition	1 year	There is often too much delay between data acquisition and reporting the processed data to the WGMS (usually ca. 2 years). This has been recently improved (partly) through the early submission of preliminary data in about 1 yr after data collection (though the data quality should not be compromised).
FoG database: Point surface mass balance (UPM)	Data are accessible some years after acquisition	1 year	Same comment as above for the glacier-wide surface mass balance.
FoG database: Point snow density (UPM)	some years after acquisition	1 year	Same comment as above for the glacier-wide surface mass balance.
GlaThiDa: Glacier Ice Thickness (UPM)	some years after acquisition	< 1 year	There is often too much delay (from several to many years) between data acquisition and public availability of the processed data. Moreover, only a small subset of the available ice-thickness data is provided to the GlaThiDa database. This has tremendously improved with campaigns such as the IceBridge Operation.
RGI: Glacier outlines (UPM)	some years after acquisition	< 1 year	Fortunately, it is becoming more and more usual to have shorter turnaround times between data acquisition and public availability of them.
GLISN (GEUS)	Most data are accessible in real time, but some are collected with up to one year delay.	1 hour	The data that is delayed for several months add additional need for resources, since in the processing of these also require reprocessing of real time data.
NNSN (UiB)	real time	1 hour	Requirements filled

3D surface displacement from GPS (DTU)	real time	1 month	Requirements filled
AIRMETH_turbulent_fluxes_Polar5	after an unknown period	9 months after campaign	Timeliness has to be standardized.
Front positions of tidewater glaciers in Hornsund (S Svalbard)	after an unknown period	7 d 1 m 1 y	Data accessibility doesn't meet requirements
Earthquake catalogue	After preliminary processing after days or weeks, post processed data after 2 years.	For disaster management: 4-24 hours. For natural hazard evaluation 2-5 years.	Data meets the requirements for disaster managements in some regions, but not in all. Data meets the timeliness requirements for natural hazard evaluations.
Arctic-HYCOS GRDC archive	GRDC Archive data updated once per year for most countries. However, several stations are still missing in the GRDC Arctic-HYCOS Archive database. Provisional data updated daily available online from Canada, Finland, Norway, and USA, and through email request from Iceland.	Archive data updated within 1 year after end of observing year. Provisional data updated daily (at the national hydrological services)	The timeliness of the Arctic-HYCOS data collections could be substantially improved. The current situation might be good enough for climate change impact analysis, but not for real-time analysis and forecasting.

4.2.3 Gaps in uncertainty characterization

This section describes and analyses the gaps in data collection uncertainty characterization. Data traceability, comparability, standards, validation, uncertainty quantification and routine quality monitoring are assessed for each data collection and classified on a scale from 1 to 6. Criteria are explained below as in the questionnaire B.

Data traceability is the property of the result of a measurement whereby it can be related to stated references, usually national or international standards such as SI units, through an unbroken chain of comparisons and processing procedures all having stated uncertainties.

1. None
2. Comparison to independent stable measurement or local secondary standard undertaken irregularly
3. As in (2) + independent measurement / local secondary standard is itself regularly calibrated against a recognized primary standard
4. As in (3) + processing steps in the chain of traceability are documented but not yet fully quantified
5. As in (4) + traceability in the processing chain partly established
6. As in (5) + traceability in the processing chain fully established

Data comparability evaluates the extent to which the data collection has been validated to provide realistic uncertainty estimates and stable operations through in-the-field comparisons.

1. None
2. Validation using external comparator measurements done only periodically and these comparator measurements lack traceability
3. As in (2) + Validation is done sufficiently regularly to ascertain gross systematic drift effects
4. As in (3) + (Inter)comparison against corresponding measurements in large-scale instrument intercomparison campaigns
5. As in (4) + compared regularly to at least one measurement that has traceability as in (5) or (6)
6. As in (5) + compared periodically to additional measurements including some with mature traceability

Standards is only applied to derived data products, e.g. for data collections that result from summarized individual measurements or are composed of integrated measurements (for instance, pan-Arctic climatological time series). To support a claim of traceability, the provider of a measurement result or value of a standard must document the measurement process or system used to establish the claim and provide a description of the chain of comparisons that were used to establish a connection to a particular stated reference.

1. None
2. Standard uncertainty nomenclature is identified or defined
3. As in (2) + Standard uncertainty nomenclature is applied
4. As in (3) + Procedures to establish SI traceability are defined
5. As in (4) + SI traceability partly established.

6. As in (5) + SI traceability established

Validation is only to be answered for derived data products, It evaluates the extent to which the product has been validated to provide uncertainty estimates).

1. None
2. Validation against external reference data done for limited locations and times
3. Validation using external reference data done for global and temporal representative locations and times
4. As in (3) + intercomparison against corresponding data records
5. As in (4) + data provider participated in one international data quality assessment
6. As in (4) + data provider participated in multiple international data assessments and incorporated feedbacks into the product development cycle

Uncertainty quantification evaluates the extent to which uncertainties have been fully quantified and their ease of use.

1. None
2. Limited information on uncertainty arising from systematic and random effects in the measurement
3. Comprehensive information on uncertainty arising from systematic and random effects in the measurement
4. As in (3) + quantitative estimates of uncertainty provided within the measurement products characterizing more or less uncertain data points
5. As in (4) + systematic effects removed and uncertainty estimates are partially traceable
6. As in (5) + comprehensive validation of the quantitative uncertainty estimates

Routine quality monitoring is the monitoring of data quality while processing the data.

1. None
3. Methods for routine quality monitoring defined
4. As in (3) + Routine monitoring partially implemented
5. As in (4) + Monitoring fully implemented at all production levels
6. As in (5) + Routine monitoring in place with results fed back to other accessible information, e.g. metadata or documentation

A synthesis of data collections uncertainty characterization is presented in Table 20. The overall system uncertainty gaps are identified and presented in Table 21.

Table 20. Uncertainty characterization matrix (in color scale: Maturity Level 1, Maturity level 2, Maturity level 3, Maturity level 4, Maturity level 5, Maturity level 6). Missing answers are marked in grey (Missing).

Data collection	**Data traceability**	**Data comparability**	**Standards**	**Validation**	**Uncertainty quantification**	**Routine quality monitoring**
Eddy flux data (CO_2 and CH_4) (USFD, MPG, U Exeter)	2	2	3	2	2	2
Data collection "Temperature profiles of the soil/peat layers at Russian Arctic stations" (PEEX, UHEL)	2	2	1	1	2	1
ERA-CLIM2 in situ SWE (FMI)	1	1	1	2	2	1
Precipitation, snow depth, air temperature from AWS in Finland (FMI)	5	6			3	5
Manual SYNOP observations (FMI)	2	3			3	3
Snow scale SWE (FMI)	2	3			3	1
Soil frost stations (FMI)	2	2			2	3
AIRMETH_turbulent_fluxes_Polar5 (GFZ)	2	3			4	3
Snow cover - Hornsund glaciers (USlaski)	2	3			2	2
Front velocity of tidewater glaciers (USlaski)	2	3			2	2
Hornsund snow cover monitoring on tundra (IGPAN)	2	3	2	2	2	2
FoG database: Glacier-wide surface mass balance (UPM)			3	3	3	3
FoG database: Point surface mass balance (UPM)			3	3	3	3
FoG database: Point snow density (UPM)			3	3	3	3
GlaThiDa: Glacier Ice Thickness (UPM)			3	3	3	3
RGI: Glacier outlines (UPM)			3	3	3	3
GLISN (GEUS)	5	5	6	3	3	6
NNSN (UiB)	6	6			6	6
3D surface displacement from GPS (DTU)	6	6	6	6	6	6
Front positions of tidewater glaciers in Hornsund (S Svalbard)	2	3			2	2
Earthquake catalogue	4	3	5		5	5
Arctic-HYCOS GRDC archive	4	3	n/a	n/a	2	4

Table 21. Uncertainty

Data collection	Uncertainty of observations	Required uncertainty	Comparison: observed vs required
Eddy flux data (CO_2 and CH_4) (USFD, MPG, U Exeter)	The uncertainty is not quantifiable in a standardized way across sites given different instruments, set-up, and different instrumental maintenance in different sites	standardized uncertainties estimates across sites (this would required a standardized set-up of the instrument)	Standardization is lacking
Data collection “Temperature profiles of the soil/peat layers at Russian Arctic stations” (PEEX, UHEL)	Limited information on uncertainty arising from systematic and random effects in the measurement	temperature +/- 0.1 C across 11 measurement sites the standardized uncertainties estimates would be desirable	automated quality monitoring of measurements will be desired
ERA-CLIM2 in situ SWE (FMI)	Limited information on uncertainty arising from systematic and random effects in the measurement	5 mm. Standardized instrumentation and methods to provide standardized uncertainty	Instruments and methods vary between countries. Uncertainty estimate depends on type of snow tube and methods used.
Snow depth from AWS in Finland (FMI)	snow depth +/- 1 cm	snow depth +/- 0.1 cm	First snow and snow on/off cases are difficult to detect. Next generation of instruments will probably increase accuracy.
Snow depth from Manual SYNOP observations (FMI)	+/- 1 cm	+/- 1 cm	Requirements filled.
Snow scale SWE (FMI)	3 mm	3 mm	Requirements filled.
Soil frost stations (FMI)	Limited information, dielectric constant +/- 15 %, soil temperature +/- 1 C, snow temperature +/- 0.2 C		Soil measurements could be more accurate
AIRMETH_turbulent_fluxes_Polar5 (GFZ)	~30%	30 %	The majority of the data fulfill the requirement
Snow cover - Hornsund glaciers (USlaski)	Limited information on uncertainty arising from systematic and random effects in the measurement	0,01 m 0,05 m 0,10 m	Detailed elaboration on uncertainty of observations needed
Front velocity of tidewater glaciers (USlaski)	Limited information on uncertainty arising from systematic and random effects in the measurement	1 m/y 5 m/y 10 m/y	Detailed elaboration on uncertainty of observations needed
Hornsund snow cover monitoring on tundra (IGPAN)	+/- 1 cm	+/- 1 cm	Requirements filled.

FoG database: Glacier-wide surface mass balance (UPM)	0.1-0.3 m w.e.	0.2 m w.e.	Uncertainty close to specifications, though variable from glacier to glacier
FoG database: Point surface mass balance (UPM)	0.1-0.3 m w.e.	0.2 m w.e.	Uncertainty close to specifications, though variable from glacier to glacier
FoG database: Point snow density (UPM)	15-25 kg/m3	10 kg/m3	To be improved through careful measurements in snow pits
GlaThiDa: Glacier Ice Thickness (UPM)	5-10%	5%	Uncertainty close to specifications, but dependent on glacier conditions (melting) and frequency of radar used
RGI: Glacier outlines (UPM)	Depending on region. Typically 5-15 m, but can be up to 60 m.	5-10 m	Specifications most often met with current satellite data available
GLISN (GEUS)	Timing: App. 1ms	Amplitude: Below MLNM (McNamara and Buland, 2004)	Requirements filled
NNSN (UiB)	Timing: App. 1ms	Amplitude: Below MLNM (McNamara and Buland, 2004)	Requirements filled
3D surface displacement from GPS (DTU)	1-2 mm	1-2 mm	Requirements filled
Front positions of tidewater glaciers in Hornsund (Svalbard)	Limited information on uncertainty arising from systematic and random effects in the measurement.	1 m 5 m 10 m	Detailed elaboration on uncertainty of observations needed
Earthquake catalogue	Horizontal location uncertainties can be up to 50km. Vertical uncertainties can be several km to anywhere in the crust.	10km and near infrastructure less than 1km	Uncertainty is highly dependent on the density of sites in different areas, a higher number of sites lowers the uncertainty.
Arctic-HYCOS GRDC archive	Uncertainty of observations is not available in the current data collection. The Arctic-HYCOS project is aiming at providing a simplified quality index indicating the reliability of each data point (flagging for instance under-ice conditions and changes in the rating curve)	<20%	The Arctic-HYCOS data set will not provide quantitative uncertainty information. Simplified qualitative uncertainty information will be provided in the future.

4.2.4 Gaps in the metadata and documentation

This section describes and analyses the gaps in data collection metadata and documentation. Metadata standards, collection level metadata, file level metadata and quality flags are assessed for each data collection and classified on a scale from 1 to 6. The metadata maturity matrix of the assessed data collections is presented in Table 22. On the data documentation, the formal description of scientific methodology, formal validation report and formal measurement series or product user guidance are assessed for each data collection and classified on a scale from 1 to 6. The documentation maturity matrix of the assessed data collections is presented in Table 23. Criteria are explained below as in the questionnaire B.

Standards: It is considered to be good practice to follow recognized metadata standards. Unless and until an ISO standard is developed and applied the assessors' judgement will be required as to the appropriateness of the standards being adhered to.

1. No standard considered
3. Metadata standards identified and/or defined and partially but not yet systematically applied
4. As in (3) + standards systematically applied at file level and collection level.
5. As in (4) + metadata standard compliance systematically checked by the data provider
6. As in (4) + extended metadata that could be useful but is not considered mandatory is also retained.

Collection level metadata includes attributes that apply across the whole of a measurement series, such as processing methods (e.g., same algorithm versions), general space and time extents, creator and custodian, references, processing history, etc.

1. None
2. Limited
3. Sufficient to use and understand the data independent of external assistance.
4. As in (3) + enhanced discovery metadata
5. As in (4) + complete discovery metadata meets appropriate (at the time of assessment) international standards
6. As in (5) + regularly updated

File level metadata includes such elements as time of observation, location, measurement units, measurement specific metadata such as ground check data, measurement batch number, ambient conditions at time of observation etc.

1. None
3. Limited
4. Sufficient to use and understand the data independent of external assistance.
5. As in (4) + Limited location (station, grid point, etc.) level metadata along with unique measurement set metadata (coordinate bounds) are provided.
6. As in (5) + Complete location (station, grid point, etc.) level and measurement specific metadata.

Quality flags indicate to a data user whether the data are valid without qualification, valid but qualified/suspect, or invalid due to serious sampling or analysis problems.

Yes - Quality flags are provided
No – Quality flags are not provided.

Table 22. Metadata maturity matrix (in color scale: Maturity Level 1, Maturity level 2, Maturity level 3, Maturity level 4, Maturity level 5, Maturity level 6). Missing answers are marked in grey (Missing). The question related to Quality flags (right column) does not have the color code because it includes only two options.

Data collection	Standards	Collection level metadata	File level metadata	Quality flags
Eddy flux data (CO_2 and CH_4) (MPG, USFD, U Exeter)	1	3	3	No
Data collection "Temperature profiles of the soil/peat layers at Russian Arctic stations" (PEEX, UHEL)	4	3	4	No
AIRMETH_turbulent_fluxes_Polar5 (GFZ)	3	2	4	Yes
ERA-CLIM2 in situ SWE (FMI)	1	3	2	Yes
Precipitation, snow depth, air temperature from AWS in Finland (FMI)	1	4	3	Yes
Manual SYNOP observations (FMI)	1	4	3	Yes
Snow scale SWE (FMI)	1	4	3	Yes
Soil frost stations (FMI)	1	4	3	Yes
Snow cover - Hornsund glaciers (USlaski)		1	1	Yes
Front velocity of tidewater glaciers (USlaski)		1	1	Yes
Hornsund snow cover monitoring on tundra (IGPAN)	4	3	4	Yes
FoG database: Glacier-wide surface mass balance (UPM)	4	3	3	No
FoG database: Point surface mass balance (UPM)	4	3	3	No
FoG database: Point snow density (UPM)	4	3	3	No
GlaThiDa: Glacier Ice Thickness (UPM)	4	3	3	No
RGI: Glacier outlines (UPM)	4	3	3	No
GLISN (GEUS)	6	6	6	N/A
NNSN (UiB)	6	6	6	Yes
3D surface displacement from GPS (DTU)	5	5	5	N/A
Front positions of tidewater glaciers in Hornsund (S Svalbard)		1	1	Yes
Earthquake catalogue	5	4	5	Yes
Arctic-HYCOS GRDC archive	5	2	5	Yes

Documentation is essential for the effective use and understanding of a measurement record. There are three sub-categories to assess the completeness of user documentation:

Formal description of scientific methodology refers to a description of the physical and methodological basis of the measurements, network status (if applicable), processing of the raw data and dissemination.

1. Limited scientific description of methodology available from data collector, instrument manufacturer, or PI
2. Comprehensive scientific description available from data collector, instrument manufacturer, or PI
3. As in (2) + Journal paper on measurement methodology published
4. As in (3) + Comprehensive scientific description available from Data Provider
5. As in (4) + Comprehensive scientific description maintained by Data Provider
6. As in (e) + Journal papers on measurement series/product updates published

Formal validation report contains details on the validation activities that have been done to assess the fidelity/reliability of the data collection.

1. None
2. Informal validation work undertaken
3. Instrument has participated in certified intercomparison campaign and results available in gray literature
4. Report on intercomparison to other instruments, etc.; Journal paper or product validation published
5. As in (4) + Sustained validation undertaken via redundant periodic measurements
6. As in (5) + Journal papers describing more comprehensive validation, e.g. error covariance, validation of quantitative uncertainty estimates published

Formal measurement series or product user guidance contains details necessary for measurement users to discover and use the data in an appropriate manner.

1. None
2. Sufficient information on the data collection available to allow user to ascertain minimum set of information required for appropriate use
3. Comprehensive documentation on how the measurement is made or the product derived available from data collector or instrument manufacturer or PI, including basic data characteristics description
4. As in (3) + including documentation of manufacturer independent characterization and validation
5. As in (4) + regularly updated by data provider with instrument / method of measurement/processing updates and/or new validation results
6. As in (5) + measurement description and examples of usage available in peer-reviewed literature

Table 23. Documentation maturity matrix (in color scale: Maturity Level 1, Maturity level 2, Maturity level 3, Maturity level 4, Maturity level 5, Maturity level 6). Missing answers are marked in grey (Missing).

Data collection	Formal description of scientific methodology	Formal validation report	Formal measurement series or product user guidance
Eddy flux data (CO_2 and CH_4) (USFD, MPG, U Exeter)	3	3	3
Data collection "Temperature profiles of the soil/peat layers at Russian Arctic stations" (PEEX, UHEL)	2	2	2
AIRMETH_turbulent_fluxes_Polar5 (GFZ)	3	2	2
ERA-CLIM2 in situ SWE (FMI)	1	1	1
Precipitation, snow depth, air temperature from AWS in Finland (FMI)	1	2	2
Manual SYNOP observations (FMI)	1	2	2
Snow scale SWE (FMI)	2	4	2
Soil frost stations (FMI)	1	3	3
Snow cover - Hornsund glaciers (USlaski)	3	2	2
Front velocity of tidewater glaciers (USlaski)	1	2	2
Hornsund snow cover monitoring on tundra (IGPAN)	1	2	2
FoG database: Glacier-wide surface mass balance (UPM)	3	2	3
FoG database: Point surface mass balance (UPM)	3	2	3
FoG database: Point snow density (UPM)	3	2	3
GlaThiDa: Glacier Ice Thickness (UPM)	3	2	3
RGI: Glacier outlines (UPM)	3	2	3
GLISN (GEUS)	6	6	6
NNSN (UiB)	6	4	5
3D surface displacement from GPS (DTU)	6	5	5
Front positions of tidewater glaciers in Hornsund (S Svalbard)	3	2	2
Earthquake catalogue	5	2	2

Arctic-HYCOS GRDC archive	1	1	2

4.3 Satellite products

In this section, selected terrestrial and cryospheric satellite products are assessed with respect to spatial/temporal coverage and resolution (Sect 4.3.2), timeliness (Sect 4.3.3), uncertainty (4.3.4), metadata and documentation (Sect. 4.3.5) and data management (Sect 4.3.6). Knowledge gaps are identified through maturity matrices and comparison between the data characteristics and the requirements defined in Sect 3.

4.3.1 General information

Table 24 provides general information related to the addressed terrestrial and cryospheric satellite products.

Table 24. Assessed terrestrial and cryospheric satellite products

Satellite Products	Data assessor	Instrument	Platform	Data Centres and Archives	Coordinating Bodies
AMSR-E/Aqua Daily L3 Global SWE v2	Anna Kontu (FMI)	AMSR-E	Aqua	NSIDC http://nsidc.org/	FMI
ERA-CLIM2 NH SWE	Anna Kontu (FMI)	SMMR SSM/I AMSR-E	Nimbus-7 DMSP Aqua	http://litdb.fmi.fi/eraclim2.php	FMI
ESA DUE GlobSnow v2.0 SWE	Anna Kontu (FMI)	SMMR SSM/I AMSR-E	Nimbus-7 DMSP Aqua	www.globsnow.info	FMI
GlobSnow snow extent	Anna Kontu (FMI)	ATSR-2 AATSR	ERS-2 Envisat	www.globsnow.info	FMI
IMS Daily NH Snow and Ice Analysis	Anna Kontu (FMI)	AMSU-A, ATMS, AVHRR, GOES I-M IMAGER, MODIS, MTSAT 1R Imager, MTSAT 2 Imager, MVIRI, SAR, SEVIRI, SSM/I, SSMIS, VIIRS	AQUA, DMSP, DMSP 5D-3/F17, GOES-10, GOES-11, GOES-13, GOES-9, METEOSAT, MSG, MTSAT-1R, MTSAT-2, NOAA-14, NOAA-15, NOAA-16, NOAA-17, NOAA-18, NOAA-N, RADARSAT-2, SUOMI-NPP, TERRA	http://nsidc.org/data/G02156	FMI
JASMES snow depth	Anna Kontu (FMI)	AMSR2	GCOM-W1	http://kuroshio.eorc.jaxa.jp/JASMES/WC.html	FMI
MODIS/Aqua Snow cover daily L3	Anna Kontu (FMI)	MODIS	Aqua	http://nsidc.org	FMI

SMAP L3 Radiometer NH daily freeze/thaw state	Anna Kontu (FMI)	L-band radiometer	SMAP	http://nsidc.org	FMI
GRACE Gravity - Ice Sheet Mass Change	Shfaqat Abbas Khan, DTU	mapping variations in Earth's gravity field		https://www.nasa.gov/mission_pages/Grace/overview/index.html	DTU
SMOS soil frost	FMI	SMOS	SMOS		FMI
Ice Sheet Surface Velocity Maps	GEUS	C-SAR (Synthetic Aperture Radar working in C-band)	Sentinel-1A & -1B	www.promice.org	GEUS
Ice Sheet Mass Change from GRACE and GNET	DTU	Satellite gravity and GPS	Gravity Recovery and Climate Experiment (GRACE)		DTU

4.3.2 Gaps in spatial and temporal coverage and resolution

This section analyses the spatio-temporal gaps in the satellite products. The requirements are set for each satellite product in Sect. 3 with criteria level **goal**, **breakthrough**, and **threshold** when relevant. In Table 25, horizontal coverage is compared with the corresponding requirements. In Table 26, spatial vertical and horizontal resolution of each satellite product is compared with the corresponding requirements. In Tables 27 and 28 the data temporal coverage (i.e. measurement time period) and temporal resolution (i.e. instrument/collection time resolution) and presented and compared with the corresponding requirements.

Table 25. Spatial coverage

Product	Horizontal coverage of observations	Required horizontal coverage	Comparison: observed vs required
AMSR-E/Aqua Daily L3 Global SWE v2	Global	Global	Requirements filled.
ERA-CLIM2 NH SWE	NH, latitudes between 35° and 85°	Global	Only NH.
ESA DUE GlobSnow v2.0 SWE	NH, latitudes between 40° and 90°	Global	Only NH.
GlobSnow snow extent	Global (excluding glaciers, Greenland, Antarctica and snow on ice)	Global	Requirements filled (mostly)
IMS Daily NH Snow and Ice Analysis	Global	Global	Requirements filled.
JASMES snow depth	Global	Global	Requirements filled.
MODIS/Aqua Snow Cover Daily L3	Global	Global	Requirements filled.
SMAP L3 Radiometer NH Daily Freeze/Thaw State	NH, latitudes between 45° and 85°	Global	Only NH.

GRACE Gravity - Ice Sheet Mass Change	Global	Lat: 58-84 degs N, Lon: 10-75 degs W	Good correspondence
SMOS soil frost	Global	Global land	Global satellite data available. About top 10 cm of soil can be measured with this method.
Ice Sheet Surface Velocity Maps	Lat: 60-84 degs N, Lon: 10-75 degs W (Greenland (Mainly the margins))	Lat: 60-84 degs N, Lon: 10-75 degs W (Greenland (Mainly the margins))	Good correspondence
Ice Sheet Mass Change from GRACE and GNET	Greenland	Lat: 58-84 degs N, Lon: 10-75 degs W	Good correspondence

Table 26. Spatial resolution

Product	Horizontal resolution of observations	Required horizontal resolution	Comparison: observed vs required
AMSR-E/Aqua Daily L3 Global SWE v2	25 km	< 5 km	5 km for most applications, 0.5 km for high-res nowcasting and 0.1 km for hydrology.
ERA-CLIM2 NH SWE	25 km	< 5 km	5 km for most applications, 0.5 km for high-res nowcasting and 0.1 km for hydrology.
ESA DUE GlobSnow v2.0 SWE	25 km	< 5km	5 km for most applications, 0.5 km for high-res nowcasting and 0.1 km for hydrology.
GlobSnow snow extent	1 km globally for 1995-1999; from 2000 1 km globally and 250-500 m for complex terrain	1 km	Required resolution highly varies with application from 0.1 km (hydrology) to 100 km (climate-AOPC). For most applications 1 km resolution is enough.
IMS Daily NH Snow and Ice Analysis	1 km, 4 km, 24 km	1 km	Required resolution highly varies with application from 0.1 km (hydrology) to 100 km (climate-AOPC). For most applications 1 km resolution is enough.
JASMES snow depth	0.25°, 0.1°	5 km	0.25°=27 km at equator, less closer to poles.
MODIS/Aqua Snow Cover Daily L3	500 m	1 km	Required resolution highly varies with application from 0.1 km (hydrology) to 100 km (climate-AOPC). For most applications 1 km resolution is enough.
SMAP L3 Radiometer NH Daily Freeze/Thaw State	9 km, 36 km	0.1 km 1 km 100 km	Threshold requirement reached
GRACE Gravity - Ice Sheet Mass Change	250 x 250 km	250 x 250 km	Good correspondence

SMOS soil frost	43 km	0.1 km 1 km 100 km	Threshold requirement reached for hydrological studies, but better horizontal resolution is desirable.
Ice Sheet Surface Velocity Maps	500 m	50 m 100-1000 m	Good corresponce between observed and required horisontal resolution.
Ice Sheet Mass Change from GRACE and GNET	150 x 150 km	150 x 150 km	Good correspondence

Table 27. Temporal coverage

Product	Temporal coverage of observations	Required temporal coverage	Comparison: observed vs required
AMSR-E/Aqua Daily L3 Global SWE v2	start: 2002.06.19, end: 2011.10.03	> 20 y for climate studies	Ok for assimilation in operational models but not for climate application
ERA-CLIM2 NH SWE	start: 1979.09.11, end: 2016.05.31	> 20 y for climate studies	Requirements fulfilled.
ESA DUE GlobSnow v2.0 SWE	start: 1978	> 20 y for climate studies	Requirements fulfilled.
GlobSnow snow extent	start: 1995.06.02	> 20 y for climate studies	Requirements fulfilled
IMS Daily NH Snow and Ice Analysis	start: 1997.02.04	> 20 y for climate studies	Requirements fulfilled
JASMES snow depth	start: 2012.07.04	> 20 y for climate studies	Ok for assimilation in operational models but not for climate application
MODIS/Aqua Snow Cover Daily L3	start: 2002.07.04	> 20 y for climate studies	Ok for assimilation in operational models but not for climate application
SMAP L3 Radiometer NH Daily Freeze/Thaw State	start: 2015.03.31	> 20 y for climate studies	Ok for assimilation in operational models but not for climate application
GRACE Gravity - Ice Sheet Mass Change	2003-2017	2003-2017	Good correspondence
SMOS soil frost	start: 2010.02.01	> 20 y for climate studies	Ok for assimilation in operational models but not for climate application
Ice Sheet Surface Velocity Maps	2017.09.12 (start) - ongoing	All year coverage	Good
Ice Sheet Mass Change from GRACE and GNET	2007-2018	2007-2018	Good

Table 28. Temporal resolution

Product	**Temporal resolution of observations**	**Required temporal resolution**	**Comparison: observed vs required**
AMSR-E/Aqua Daily L3 Global SWE v2	1 day	1 h (high-res NWP), 3 h (global NWP), 1 day	Higher resolution needed for NWP.
ERA-CLIM2 NH SWE	1-15 days (recent data daily, gaps in the beginning due to unavailability of satellite data)	1 h (high-res NWP), 3 h (global NWP), 1 day	Higher resolution needed for NWP.
ESA DUE GlobSnow v2.0 SWE	1 day, 7 days, 30 days	1 h (high-res NWP), 3 h (global NWP), 1 day	Higher resolution needed for NWP.
GlobSnow snow extent	1 day, 7 days, 30 days	1 h (high-res NWP), 3 h (global NWP), 1 day	Higher resolution needed for NWP.
IMS Daily NH Snow and Ice Analysis	Daily	1 h (high-res NWP), 3 h (global NWP), 1 day	Higher resolution needed for NWP.
JASMES snow depth	L2 every granule, L3 daily	1 h (high-res NWP), 3 h (global NWP), 1 day	Higher resolution needed for NWP.
MODIS/Aqua Snow Cover Daily L3	Daily	1 h (high-res NWP), 3 h (global NWP), 1 day	Higher resolution needed for NWP.
SMAP L3 Radiometer NH Daily Freeze/Thaw State	Daily		
GRACE Gravity - Ice Sheet Mass Change	1 month	1 month	Good correspondence
SMOS soil frost	1 day	2 days 1 day 1 day	Requirements fulfilled
Ice Sheet Surface Velocity Maps	6-12 days	Monthly Annual	Requirements fulfilled
Ice Sheet Mass Change from GRACE and GNET	1 day	1 day	Requirements fulfilled

4.3.3 Gaps in timeliness

This section analyses the timeliness of the satellite products. The requirements are set in Sect. 3.

Table 29. Timeliness

Product	Timeliness of observations	Required timeliness	Comparison: observed vs required
AMSR-E/Aqua Daily L3 Global SWE v2	n/a	1 h, 3 h , 1 day	All data available. No new data available, as instrument is not working anymore. Only occasional updates to processing algorithms.
ERA-CLIM2 NH SWE	n/a	1 h, 3 h , 1 day	Project finished, no new updates.
ESA DUE GlobSnow v2.0 SWE	6 months	1 h, 3 h , 1 day	Not met requirements
GlobSnow snow extent	1 day	1 h, 3 h , 1 day	Met threshold requirement
IMS Daily NH Snow and Ice Analysis	1 day	1 h, 3 h , 1 day	Met threshold requirement
JASMES snow depth	1 week	1 h, 3 h , 1 day	Not met requirements
MODIS/Aqua Snow Cover Daily L3	1 day	1 h, 3 h , 1 day	Met threshold requirement
SMAP L3 Radiometer NH Daily Freeze/Thaw State	1 day		
GRACE Gravity - Ice Sheet Mass Change	1 month	real time	Not met requirements
SMOS soil frost	Unknown	1 day	Data not yet publicly available
Ice Sheet Surface Velocity Maps	6 months	1 week, 1 month, 1 year	Met threshold requirement
Ice Sheet Mass Change from GRACE and GNET	unknown	real time	unknown

4.3.4 Gaps in uncertainty characterization

This section describes and analyses the gaps in data collection uncertainty characterization. Data traceability, comparability, standards, validation, uncertainty quantification and routine quality monitoring are assessed for each data collection and classified on a scale from 1 to 6. Criteria are explained below as in the questionnaire C. A synthesis of data collections uncertainty characterization is presented in Table 26. The overall system uncertainty gaps are identified and presented in Table 27.

Standards: There are no international standards as such available for uncertainty characterization. However, there is a compelling need for this. Uncertainty arising from systematic and random effects in the measurements shall be provided for each step of the product generation. In the end, it shall be related to reference data. As absolute references are not readily available, measurements may be taken as reference if their accuracy is about one order of magnitude better compared to the measurement that is assessed.

1. None
2. Standard uncertainty nomenclature is identified or defined
3. As in (2) + Standard uncertainty nomenclature is applied
4. As in (3) + Procedures to establish SI traceability are defined
5. As in (4) + SI traceability partly established
6. As in (5) + SI traceability established

Validation evaluates the extent to which the product has been validated to provide uncertainty estimates.

1. None
2. Validation against external reference data done for limited locations and times
3. Validation using external reference data done for global and temporal representative locations and times
4. As in (3) + intercomparison against corresponding data records (other methods, models, etc.)
5. As in (4) + data provider participated in one international data quality assessment
6. As in (5) + data provider participated in multiple international data assessments and incorporated feedbacks into the product development cycle

Uncertainty quantification evaluates the extent to which uncertainties have been quantified.

1. None
2. Limited information on uncertainty arising from systematic and random effects in the measurement
3. Comprehensive information on uncertainty arising from systematic and random effects in the measurement.
4. As in (3) + quantitative estimates of uncertainty provided within the measurement products characterizing more or less uncertain data points.
5. As in (4) + systematic effects removed and uncertainty estimates are partially traceable (spatial and temporal error covariance are quantified)
6. As in (5) comprehensive validation of the quantitative uncertainty estimates (the uncertainty estimates are validated using superior quality datasets

Automated quality monitoring is the monitoring of data quality while processing the data.

1. None.
3. Method for automated quality monitoring defined.
4. As in (2) + automated monitoring partially implemented
5. As in (3) + monitoring fully implemented (all production levels)

6. As in (4) + automated monitoring in place with results fed back to other accessible information, e.g. metadata or documentation

A synthesis of data collections uncertainty characterization is presented in Table 26. The overall system uncertainty gaps are identified and presented in Table 27

Table 26. Uncertainty characterization matrix (in color scale: Maturity Level 1, Maturity level 2, Maturity level 3, Maturity level 4, Maturity level 5, Maturity level 6). Missing answers are marked in grey (Missing).

Product	**Standards**	**Validation**	**Uncertainty quantification**	**Automated quality monitoring**
AMSR-E/Aqua Daily L3 Global SWE v2	2	4	3	5
ERA-CLIM2 NH SWE	3	4	6	5
ESA DUE GlobSnow v2.0 SWE	2	4	4	4
GlobSnow snow extent	3	4	3	5
IMS Daily NH Snow and Ice Analysis	1	4	2	5
JASMES snow depth	3	3	2	3
MODIS/Aqua Snow Cover Daily L3	3	3	3	6
SMAP L3 Radiometer NH Daily Freeze/Thaw State	2	3	2	5
GRACE Gravity - Ice Sheet Mass Change	5	5	5	5
SMOS soil frost	1	3	2	4
Ice Sheet Surface Velocity Maps	4	3	2	4
Ice Sheet Mass Change from GRACE and GNET	2	2	3	1

Table 27. Temporal coverage

Product	**Temporal coverage of observations**	**Required temporal coverage**	**Comparison: observed vs required**
AMSR-E/Aqua Daily L3 Global SWE v2	start: 2002.06.19, end: 2011.10.03	> 20 y for climate studies	Ok for assimilation in operational models but not for climate application
ERA-CLIM2 NH SWE	start: 1979.09.11, end: 2016.05.31	> 20 y for climate studies	Requirements fulfilled.
ESA DUE GlobSnow v2.0 SWE	start: 1978	> 20 y for climate studies	Requirements fulfilled.
GlobSnow snow extent	start: 1995.06.02	> 20 y for climate studies	Requirements fulfilled
IMS Daily NH Snow and Ice Analysis	start: 1997.02.04	> 20 y for climate studies	Requirements fulfilled

JASMES snow depth	start: 2012.07.04	> 20 y for climate studies	Ok for assimilation in operational models but not for climate application
MODIS/Aqua Snow Cover Daily L3	start: 2002.07.04	> 20 y for climate studies	Ok for assimilation in operational models but not for climate application
SMAP L3 Radiometer NH Daily Freeze/Thaw State	start: 2015.03.31	> 20 y for climate studies	Ok for assimilation in operational models but not for climate application
GRACE Gravity - Ice Sheet Mass Change	2003-2017	2003-2017	Good correspondence
SMOS soil frost	start: 2010.02.01	> 20 y for climate studies	Ok for assimilation in operational models but not for climate application
Ice Sheet Surface Velocity Maps	2017.09.12 (start) - ongoing	All year coverage	Good
Ice Sheet Mass Change from GRACE and GNET	2007-2018	2007-2018	Good

Table 28. Temporal resolution

Product	Temporal resolution of observations	Required temporal resolution	Comparison: observed vs required
AMSR-E/Aqua Daily L3 Global SWE v2	1 day	1 h (high-res NWP), 3 h (global NWP), 1 day	Higher resolution needed for NWP.
ERA-CLIM2 NH SWE	1-15 days (recent data daily, gaps in the beginning due to unavailability of satellite data)	1 h (high-res NWP), 3 h (global NWP), 1 day	Higher resolution needed for NWP.
ESA DUE GlobSnow v2.0 SWE	1 day, 7 days, 30 days	1 h (high-res NWP), 3 h (global NWP), 1 day	Higher resolution needed for NWP.
GlobSnow snow extent	1 day, 7 days, 30 days	1 h (high-res NWP), 3 h (global NWP), 1 day	Higher resolution needed for NWP.
IMS Daily NH Snow and Ice Analysis	Daily	1 h (high-res NWP), 3 h (global NWP), 1 day	Higher resolution needed for NWP.
JASMES snow depth	L2 every granule, L3 daily	1 h (high-res NWP), 3 h (global NWP), 1 day	Higher resolution needed for NWP.
MODIS/Aqua Snow Cover Daily L3	Daily	1 h (high-res NWP), 3 h (global NWP), 1 day	Higher resolution needed for NWP.
SMAP L3 Radiometer NH Daily Freeze/Thaw State	Daily	6 h 14 h 3 day	Threshold requirement fulfilled

GRACE Gravity - Ice Sheet Mass Change	1 month	1 month	Requirement fulfilled
SMOS soil frost	1 day	6 h 14 h 3 day	Threshold requirement fulfilled
Ice Sheet Surface Velocity Maps	6-12 days	Monthly Annual	Requirement fulfilled
Ice Sheet Mass Change from GRACE and GNET	1 day	1 day	Requirement fulfilled

4.3.3 Gaps in timeliness

This section analyses the timeliness of the satellite products. The requirements are set in Sect. 3.

Table 29. Timeliness

Product	Timeliness of observations	Required timeliness	Comparison: observed vs required
AMSR-E/Aqua Daily L3 Global SWE v2	n/a	1 h, 3 h , 1 day	All data available. No new data available, as instrument is not working anymore. Only occasional updates to processing algorithms.
ERA-CLIM2 NH SWE	n/a	1 h, 3 h , 1 day	Project finished, no new updates.
ESA DUE GlobSnow v2.0 SWE	6 months	1 h, 3 h , 1 day	Requirements are not met
GlobSnow snow extent	1 day	1 h, 3 h , 1 day	Met threshold requirement
IMS Daily NH Snow and Ice Analysis	1 day	1 h, 3 h , 1 day	Met threshold requirement
JASMES snow depth	1 week	1 h, 3 h , 1 day	Not met requirements
MODIS/Aqua Snow Cover Daily L3	1 day	1 h, 3 h , 1 day	Met threshold requirement
SMAP L3 Radiometer NH Daily Freeze/Thaw State	1 day	6 h 17 h 6 day	Met threshold requirement
GRACE Gravity - Ice Sheet Mass Change	1 month	real time	Not met requirements
SMOS soil frost	Unknown	6 h 17 h 6 day	Data not yet publicly available
Ice Sheet Surface Velocity Maps	6 months	1 week, 1 month, 1 year	Threshold requirement are met
Ice Sheet Mass Change from GRACE and GNET	Unknown	real time	Unknown

4.3.4 Gaps in uncertainty characterization

This section describes and analyses the gaps in uncertainty characterization. Data traceability, comparability, standards, validation, uncertainty quantification and routine quality monitoring are assessed for each satellite product and classified on a scale from 1 to 6. Criteria are explained below as in the questionnaire C. A synthesis of uncertainty characterization is presented in Table 30. The overall uncertainty gaps of the satellite products are identified and presented in Table 31.

Standards: There are no international standards as such available for uncertainty characterization. However, there is a compelling need for this. Uncertainty arising from systematic and random effects in the measurements shall be provided for each step of the product generation. In the end, it shall be related to reference data. As absolute references are not readily available, measurements may be taken as reference if their accuracy is about one order of magnitude better compared to the measurement that is assessed.

7. None
8. Standard uncertainty nomenclature is identified or defined
9. As in (2) + Standard uncertainty nomenclature is applied
10. As in (3) + Procedures to establish SI traceability are defined
11. As in (4) + SI traceability partly established
12. As in (5) + SI traceability established

Validation evaluates the extent to which the product has been validated to provide uncertainty estimates.

7. None
8. Validation against external reference data done for limited locations and times
9. Validation using external reference data done for global and temporal representative locations and times
10. As in (3) + intercomparison against corresponding data records (other methods, models, etc.)
11. As in (4) + data provider participated in one international data quality assessment
12. As in (5) + data provider participated in multiple international data assessments and incorporated feedbacks into the product development cycle

Uncertainty quantification evaluates the extent to which uncertainties have been quantified.

7. None
8. Limited information on uncertainty arising from systematic and random effects in the measurement
9. Comprehensive information on uncertainty arising from systematic and random effects in the measurement.
10. As in (3) + quantitative estimates of uncertainty provided within the measurement products characterizing more or less uncertain data points.
11. As in (4) + systematic effects removed and uncertainty estimates are partially traceable (spatial and temporal error covariance are quantified)
12. As in (5) comprehensive validation of the quantitative uncertainty estimates (the uncertainty estimates are validated using superior quality datasets

Automated quality monitoring is the monitoring of data quality while processing the data.

2. None.
7. Method for automated quality monitoring defined.
8. As in (2) + automated monitoring partially implemented
9. As in (3) + monitoring fully implemented (all production levels)
10. As in (4) + automated monitoring in place with results fed back to other accessible information, e.g. metadata or documentation

A synthesis of data collections uncertainty characterization is presented in Table 26. The overall system uncertainty gaps are identified and presented in Table 27

Table 30. Uncertainty characterization matrix (in color scale: Maturity Level 1, Maturity level 2, Maturity level 3, Maturity level 4, Maturity level 5, Maturity level 6). Missing answers are marked in grey (Missing).

Product	Standards	Validation	Uncertainty quantification	Automated quality monitoring
AMSR-E/Aqua Daily L3 Global SWE v2	2	4	3	5
ERA-CLIM2 NH SWE	3	4	6	5
ESA DUE GlobSnow v2.0 SWE	2	4	4	4
GlobSnow snow extent	3	4	3	5
IMS Daily NH Snow and Ice Analysis	1	4	2	5
JASMES snow depth	3	3	2	3
MODIS/Aqua Snow Cover Daily L3	3	3	3	6
SMAP L3 Radiometer NH Daily Freeze/Thaw State	2	3	2	5
GRACE Gravity - Ice Sheet Mass Change	5	5	5	5
SMOS soil frost	1	3	2	4
Ice Sheet Surface Velocity Maps	4	3	2	4
Ice Sheet Mass Change from GRACE and GNET	2	2	3	1

Table 31. Uncertainty

Product	**Uncertainty of observations**	**Required uncertainty**	**Comparison: observed vs required**
AMSR-E/Aqua Daily L3 Global SWE v2	Unknown	2 mm (global NWP), 5 mm	Uncertainty of satellite products is far from what is needed in NWP.
ERA-CLIM2 NH SWE	40 mm	2 mm (global NWP), 5 mm	Uncertainty of satellite products is far from what is needed in NWP.
ESA DUE GlobSnow v2.0 SWE	~30-35 mm, if SWE < 150 mm	2 mm (global NWP), 5 mm	Uncertainty of satellite products is far from what is needed in NWP.
GlobSnow snow extent	Binary classification (snow/no-snow) with global total (pooled) error ≤ 5 % for open terrain, sparse forest and non-steep mountainous regions, at solar elevation > 20°. Temporal inference of snow in dark regions or masked as 'not observed'	2 % (agricultural meteorology), 5 % (high-res NWP, hydrology, climate-TOPC), 10 %	Requirements filled.
IMS Daily NH Snow and Ice Analysis	Unknown	2 % (agricultural meteorology), 5 % (high-res NWP, hydrology, climate-TOPC), 10 %	Impossible to assess without dedicated validation studies
JASMES snow depth	+/- 25 cm	0.1 cm	Uncertainty of satellite products is far from what is needed in NWP.

MODIS/Aqua Snow Cover Daily L3	Unknown	2 % (agricultural meteorology), 5 % (high-res NWP, hydrology, climate-TOPC), 10 %	Impossible to assess without dedicated validation studies
SMAP L3 Radiometer NH Daily Freeze/Thaw State	Unknown	5 % 8.5 % 25 %	Impossible to assess without dedicated validation studies
GRACE Gravity - Ice Sheet Mass Change	+/- 20 Gt/yr	+/- 20 Gt/yr	Good
SMOS soil frost	Unknown	Soil bearing capacity: 50 % 75 % 80 % Carbon cycle monitoring: 1 day	Impossible to assess without dedicated validation studies
Ice Sheet Surface Velocity Maps	Varies	10 m/yr 30 m/yr	Impossible to assess without dedicated validation studies
Ice Sheet Mass Change from GRACE and GNET	Unknown	Unknown	Impossible to assess without dedicated validation studies

4.3.5 Gaps in the metadata and documentation

This section describes and analyses the gaps in metadata and documentation. Metadata standards, collection level metadata and file level metadata are assessed for each data collection and classified on a scale from 1 to 6. The metadata maturity matrix of the assessed satellite products is presented in Table 32. On the data documentation, the formal description of scientific methodology, formal validation report and formal measurement series or product user guidance are assessed for each data collection and classified on a scale from 1 to 6. The documentation maturity matrix of the assessed data collections is presented in Table 33. Criteria are explained below as in the questionnaire C.

Standards: It is considered to be good practice to follow recognized metadata standards. Unless and until an ISO standard is developed and applied the assessors' judgement will be required as to the appropriateness of the standards being adhered to.

1. No standard considered
3. Metadata standards identified and/or defined and partially but not yet systematically applied
4. As in (3) + standards systematically applied at file level and collection level by data provider. Meets international standards
5. As in (4) + metadata standard compliance systematically checked by the data provider
6. As in (5) + extended metadata that could be useful but is not considered mandatory is also retained.

Collection level metadata includes attributes that apply across the whole of a dataset, such as processing methods (e.g., same algorithm versions), general space and time extents, creator and custodian, references, processing history, etc.

1. None

2. Limited
3. Sufficient to use and understand the data independent of external assistance. Sufficient for data user to extract discovery metadata from metadata repositories
4. As in (3) + enhanced discovery metadata
5. As in (4) + complete discovery metadata meets appropriate international standards
6. As in (5) + regularly updated

File level metadata includes such elements as time of observation, location, measurement units, measurement specific metadata such as ground check data, measurement batch number, ambient conditions at time of observation etc.

1. None
3. Limited
4. Sufficient to use and understand the data independent of external assistance.
5. As in (4) + Limited location (pixel, grid point, etc.) level metadata along with unique measurement set metadata
6. As in (5) + Complete location level and measurement specific metadata.

Quality flags: Reported data values must be assigned at least one data quality flag by the data originator that indicates to a data user whether the data are valid without qualification, valid but qualified/suspect, or invalid due to serious sampling or analysis problems.

1. Quality flags are not provided
2. Quality flags are provided only for some products
3. Quality flags are provided for all data products

Table 32. Metadata maturity matrix (in color scale: Maturity Level 1, Maturity level 2, Maturity level 3, Maturity level 4, Maturity level 5, Maturity level 6). Missing answers are marked in grey (Missing). The question related to Quality flags (right column) has red, yellow, and green colors corresponding to "Not provided", "Provided only for some products", and "Provided for all data products", respectively.

Product	Standards	Collection level metadata	File level metadata	Quality flags
AMSR-E/Aqua Daily L3 Global SWE v2	5	3	5	Yes
ERA-CLIM2 NH SWE	1	3	4	No
ESA DUE GlobSnow v2.0 SWE	4	3	6	No
GlobSnow snow extent	1	3	4	No
IMS Daily NH Snow and Ice Analysis	5	3	5	No
JASMES snow depth	1	3	4	Yes
MODIS/Aqua Snow Cover Daily L3	5	3	3	Partly
SMAP L3 Radiometer NH Daily Freeze/Thaw State	5	3	5	Yes
GRACE Gravity - Ice Sheet Mass Change	5	5	5	Yes
SMOS soil frost	1	3	3	No
Ice Sheet Surface Velocity Maps	2	3	4	No
Ice Sheet Mass Change from GRACE and GNET	3	3	4	No

Documentation is essential for the effective use and understanding of a measurement record. There are three sub-categories to assess the completeness of user documentation.

Formal description of scientific methodology refers to description of the physical basis of measurements, processing of the raw data to higher level (geo-location, calibration, inter-calibration, retrieval methods, and space-time averaging methods).

1. Limited scientific description of methodology available from PI
2. Comprehensive scientific description available from PI and Journal paper on methodology submitted.
3. As in (2) + Journal paper on methodology published
4. As in (3) + Comprehensive scientific description available from Data Provider
5. As in (4) + Comprehensive scientific description maintained by Data Provider
6. As in (5) + Journal papers on product updates published

Formal validation report contains details on the validation activities that have been done to assess the fidelity/reliability of the data collection. It describes uncertainty characteristics of the measurement record found through the application of uncertainty analysis, and provides all relevant references.

1. None
2. Report on limited validation available from PI; paper on product validation submitted
3. Report on comprehensive validation available from PI; Journal paper on product validation submitted.
4. Report on intercomparison to other data records, etc.; Journal paper or product validation published.
5. As in (4) + Report on data assessment results exists
6. As in (5) + Journal papers describing more comprehensive validation, e.g. error covariance, validation of quantitative uncertainty estimates published.

Formal product user guidance contains definition of the data set, requirements considered while developing the data set, overview of input data and methods, general quality remarks, validation methods and estimated uncertainty in the data, strength and weakness of the data, format and content description, references, and contact details.

1. None
3. Limited product user guide available from PI
4. Comprehensive user guide available from PI
5. As in (4) + available from data provider
6. As in (5) + regularly updated by data provider with product updates and/or new validation results

Table 33. Documentation maturity matrix (in color scale: Maturity Level 1, Maturity level 2, Maturity level 3, Maturity level 4, Maturity level 5, Maturity level 6). Missing answers are marked in grey (Missing).

Product	**Formal description of scientific methodology**	**Formal validation report**	**Formal product user guidance**
AMSR-E/Aqua Daily L3 Global SWE v2	5	1	6
ERA-CLIM2 NH SWE	4	4	1
ESA DUE GlobSnow v2.0 SWE	4	2	3
GlobSnow snow extent	5	4	5

IMS Daily NH Snow and Ice Analysis	5	1	5
JASMES snow depth	1	2	5
MODIS/Aqua Snow Cover Daily L3	3	4	5
SMAP L3 Radiometer NH Daily Freeze/Thaw State	4	4	5
GRACE Gravity - Ice Sheet Mass Change	5	5	5
SMOS soil frost	3	1	1
Ice Sheet Surface Velocity Maps	4	4	3
Ice Sheet Mass Change from GRACE and GNET	3	3	1

4.3.6 Gaps in the data management

This section describes the maturity in the data management of the satellite products. Data storage, data access, user feedback, updates to data record and version control are assessed for each data collection and classified on a scale from 1 to 6 (Table 34). Criteria are explained below as in the questionnaire C.

Data storage:

1. Data are not stored in any institutional repository, but in a personal repository such as hard-disk, computer, notebook, etc.
2. Data are stored in an institutional/departmental repository
3. Data are stored in distributed repositories(institutional and not)
4. Data are stored in a National repository according to legal constraints on their location (a specific repository is compulsory for certain data)
5. Data are stored in National data repositories without legal constraints on their location (no repository is compulsory for any data)
6. Data are stored in International data repositories

Data access: is the level of open distribution of data, documentation, and any necessary source code used to process the data. The highest scores in this category can only be attained for data provided free of charge without restrictions on use and reuse.

1. Unknown
2. Data is available on request to trusted users
2. Data is available on supervised request through originator
3. Data is available on automated request through originator
4. Data and documentation are available on supervised request through originator
5. Data and documentation are available on automated request through originator
5. Data and documentation are available through originator and recognized data portal
6. As in (5) + source data, code and metadata available upon request.
6. As in (5) + no access restrictions apply.

User feedback mechanism: Level of established mechanisms to receive, analyse and ingest user feedback.

1. None
2. Ad hoc feedback (which may be acted upon)
3. Programmatic feedback collated
4. As in (3) + consideration of published analyses
5. Established feedback mechanism and international data quality assessment results are considered

6. As in (5) + Established feedback mechanism and international data quality assessment results are considered in continuous data provisions

Updates to record: Level of systems in place to update data records when new observations or insights become available.

1. None
2. Irregularly following accrual of a number of new measurements scientific exchange and progress or new insights
4. Regularly updated with new observations and utilizing input from established feedback mechanism.
5. Regularly operationally by stable data provider as dictated by availability of new input data or new innovations.
6. As in (5) + initial version of measurement series or data products shared in near real time.

Version control: Level of a measure taken to trace back the different versions of algorithms, software, format, input and ancillary data, and documentation used to generate the data record under consideration. It allows clear statements about when and why changes have been introduced.

1. None
2. Versioning by data collector
4. Version control institutionalized and procedure documented
5. Fully established version control considering all aspects
6. As in (5) + all versions retained and accessible upon request

Table 34. Data management matrix (in color scale: Maturity Level 1, Maturity level 2, Maturity level 3, Maturity level 4, Maturity level 5, Maturity level 6). Missing answers are marked in grey (Missing).

Product	Data storage	Data access	User feedback	Updates to record	Version control
SMOS soil frost	2	2	1	2	2
Ice Sheet Surface Velocity Maps	2	5	2	4	2
Ice Sheet Mass Change from GRACE and GNET	2	2	1		
AMSR-E/Aqua Daily L3 Global SWE v2	5	5	2	5	5
ERA-CLIM2 NH SWE	2	5	2	1	5
ESA DUE GlobSnow v2.0 SWE	2	5	2	2	2
GlobSnow snow extent	2	5	2	5	5
IMS Daily NH Snow and Ice Analysis	5	5	2	5	5
JASMES snow depth	4	5	1	4	4
MODIS/Aqua Snow Cover Daily L3	5	5	2	5	5
SMAP L3 Radiometer NH Daily Freeze/Thaw State	5	5	2	5	5
GRACE Gravity - Ice Sheet Mass Change	5	5	5	5	5

5. Recommendations

5.1. Observations of greenhouse gases

With contributions from Mathias Göckede (MPG), Katrin Kohnert & Torsten Sachs (GFZ) and Donatella Zona (USFD).

The INTAROS partners involved in observations of greenhouse gas exchange processes between the terrestrial sphere and the atmosphere focused their recommendations on the following 5 major areas:

1. Need for increased temporal coverage of greenhouse gas observations,
2. Need to enhance coverage for non-CO_2 fluxes (e.g. CH_4),
3. Improved description of the spatial context of greenhouse gas flux measurements across multiple spatial scales,
4. Extended spatio-temporal observations of environmental conditions within the footprint of flux observations, with a particular focus on snow cover properties, and
5. Automated processing of flux data in near real-time, including a clear documentation of dataset characteristics and processing algorithms.

Temporal coverage: Only few of the total number of ~130 eddy-covariance flux sites in the Arctic have been operating over periods of 10 years or more, i.e. timeframes that allow the analysis of trends. Many of the locations have been discontinued, thus besides the quite large total number of sites for many ecosystems only a few years of data can be provided to date. To facilitate an improved differentiation between interannual variability and long-term trends, for those sites that are currently operating continuous support for climate-relevant timeframes should be achieved.

For most of the existing sites, including those with ongoing operations, data coverage outside the growing season is hampered by large gaps, and particularly wintertime data is often non-existing. Several studies over the past few years have demonstrated that the Arctic carbon budget is significantly influenced by emissions during the cold seasons. So besides filling gaps in the overall network coverage (with recommendations on suitable sites to be made within INTAROS WP2), the most pressing demands for improving the network performance as a whole concern the establishment of year-round operability across the network of sites.

Besides ground-based flux observations, we recommend continued aircraft eddy-covariance measurements bi-annually in Alaska and Canada and extending them to Russia and Europe to cover the major Arctic regions, and to detect interannual variability. As for the stationary eddy-covariance towers, additional measurement periods should be added in spring and autumn, to cover seasonal patterns in greenhouse gas fluxes at a high spatial resolution across the Arctic.

Non-CO_2 flux observations: While the total site coverage of eddy-covariance sites across the Arctic domain is moderate, with currently flux data available from >130 individual locations, only a small fraction of the towers measure non-CO_2 greenhouse gases. To move forward towards monitoring a total carbon budget of Arctic ecosystems, other species such as e.g. CH_4 need to be covered as well. With far less than half of the current sites covering this gas, and continuous wintertime observations only available at a very small fraction of those, the addition of sensors to capture fluxes besides fCO2 was identified as one of the most pressing issues to improve our understanding in the feedback mechanisms between global climate change and the Arctic carbon cycle.

Spatial context of observations: Many Arctic flux sites are characterized by a large variability in surface characteristics within the tower footprint, with highly polygonized Arctic tundra ecosystems as the most prominent example. Since gradients in surface characteristics, most importantly in wetness level that can dramatically change with only minor changes in topography, can exert significant influence on the observed fluxes, we recommend that an assessment of the spatial heterogeneity of the landscape should be included into the current site-level information. Multiple spatial indices should be used to define spatial heterogeneity, and their impact on variability in the observed time series of greenhouse gas fluxes should be quantified.

Along the same lines, the overall representativeness of a single tower location for the larger region should be assessed to avoid systematic biases in upscaling fluxes. The so-called sensor location bias, i.e. the difference in the spatial indices between the area sampled by the tower and the wider domain, needs to be carefully assessed, particularly for highly variable fluxes such as methane emissions. This information will reduce uncertainties in upscaling of the site-level data to the wider region, and also improve the use of the site-level data into global model validation and development. Finally, the heterogeneity of the landscape depending on ecosystem type and permafrost conditions across the Arctic should be assessed, so that targeted studies could be set up to address the role of this variability within the most heterogeneous ecosystems.

Data processing and documentation: For all greenhouse gas datasets from the Arctic domain, the time for data preparation should be reduced by possibly further automatizing data processing. This way, observations could be made available to the wider research community with only marginal time lags, so that the general public could be informed on e.g. extreme events within the Arctic, and their impact on greenhouse gas emissions, while the public attention is still high. Moreover, the documentation and publication of the data collection and processing should become publicly accessible in the near future.

5.2. Soil freezing and thawing observations

H.K. Lappalainen, A. Mahura (U Helsinki)

Recommendations on soil/pet temperature profile measurements

The continuous long-term observations in the Arctic region for basic temperature profiles of the soil/ peat layers allows to identify spatio-temporal variability in the permafrost temperature regimes in a rapidly changing climatic conditions observed in the high northern latitudes. We recommend that such observations should be continued (and larger number of observational sites to be established in the region to have a larger geographical coverage) as these observed data are important for assessing permafrost changes in a changing climate, for improvement and refining of ecosystem and climate models, for corresponding updating of the future climate scenarios, for better elaboration of decision- and policy making plans for sustainable development of Arctic regions including adaptation to climate change, socio-economical activities and protection of the environment.

Anna Kontu and Juha Lemmetyinen (FMI)

Recommendation on in situ observations from Sodankylä supersite

The soil frost stations at the Sodankylä observatory provide profiles of soil and snow temperature and soil dielectric constant. The network has been designed in particular for assessment of soil freezing and thawing processes. Stations represent the main land cover types in the region, with the purpose to enable also aggregation of the soil state to the satellite scale (validation of e.g. SMOS and SMAP retrievals of soil state). While the main land cover types are represented, spatial representation to the scale of satellite observations (~25x25 km) should still be improved by adding multiple stations within an equivalent radius, to assess spatial variability within the satellite observation. The current network in Sodankylä includes the main soil and land cover types; however, the local-scale spatial coverage (a radius < 10 km) should be further enhanced to enable the assessment of sub-pixel variability in satellite data.

Recommendation on soil freezing and thawing satellite products
Satellite datasets on seasonal soil freezing and thawing from the SMOS and SMAP sensors meet WMO OSCAR requirements in terms of observing cycle (1-5 days) and to some degree uncertainty (full assessment is still lacking). However, the horizontal resolution of satellite products (ten of kilometers) is still lacking from even the threshold requirement of 10 km.

5.3.Snow observations

Piotr Głowacki (IGPAN) and Mariusz Grabiec (USlaski)

Recommendations regarding snow cover data at the Hornsund supersite (Svalbard).
A complete dataset from Svalbard without any gaps is available only for the Hornsund station. Snow depth and SWE have been monitored at the same points by Polish expeditions since August 1982. Snow depth is calculated from a mean of three snow stakes. Information about snow depth and density in the Fuglebekken catchment is also provided from measurements managed by Polish Polar Station Hornsund personnel. These measurements started in 2013 as an additional snow monitoring program and comprise a weekly survey throughout the year of 20 points when a continuous snow cover is present on the ground. Spatial distribution of snow cover is highly variable, so measurements in other areas in Svalbard archipelago and other places should be performed for comparison.

We recommend that the spatial coverage of snow depth survey should be expanded to larger areas and glaciers of different characteristics (eg. surface topography, elevation range, exposure to the most frequent wind directions, valley width) for better representation of regional snow conditions. The spatial resolution should be improved within the limits set by the logistics and security issues of in situ observations. Vertical resolution of the snow depth measure can be considerably improved by using a higher frequency antenna, such as the 1.6 GHz HF antenna recently tested, instead of the 800 MHz antenna previously used. Finally, data storage, access, timeliness, uncertainty information and documentation should be improved.

Anna Kontu and Juha Lemmetyinen (FMI)

Recommendations for the in situ observations at the Sodankylä supersite (Finland)
The Sodankylä observatory provides continuous long time series of snow cover and other parameters of the terrestrial cryosphere from a single site, representative of the Northern boreal forest zone. Together with other data the available cryosphere datasets serve purposes of process studies and climatological assessments relevant of the site. Some basic parameters (such as snow depth, soil and snow temperature profiles) are available from a distributed network of stations, providing enhanced local and regional coverage; this enhances the reliability and representability of the data, which is required for use of the site as a reference to e.g. satellite retrievals of geophysical parameters. Data from several locations extends beyond

several decades. However, data for many parameters (such as SWE and radiative fluxes) are available only from individual and fairly recent stations.

Additionally, on a regional/hemispheric scale, data on bulk properties of seasonal snow cover (SWE/snow depth) is available from weather stations and networks operated by manual observation programs. These exhibit varying spatio-temporal coverage; an effort was made recently in the EU ERA-CLIM2 project to collect and assess these data from several sources.

The following synthesis/recommendations are made from the analyzed datasets:

1. **Snow depth from AWS and manual synoptic observations**
   Several stations report on snow depth from the Sodankylä site and surroundings, representing different land cover types and vegetation regimes. While generally the sensors (typically based on acoustic measurement of snow surface height vs. a calibrated snow free reference, with temperature correction) provide reasonable accuracy, problems arise in detection of early snowfall as well as patchiness during snow melt, which degrades the representativeness of the point-scale stations. Similar sensors are operated at ~200 stations over Finland, providing means for at least a first assessment of snow depth conditions throughout the country. The Sodankylä site is the only one (in Finland) attempting to automatically record snow conditions over different land cover types, where effects of precipitation capture (by trees) and wind transport affect the accumulated snow pack. However, considering the high variability of snow cover even at small scales, the current number of stations (total seven operational with snow depth measurements, four in Sodankylä boreal forest site and three in the Saariselkä tundra) can be considered to be a bare minimum for assessing evolution in different local snow regimes. A more comprehensive network of automated stations would be required to capture variability of snow conditions within land cover types.
2. **Snow scale SWE**
   SWE is currently obtained from a single location. Due to the high spatial variability of snow cover even at small scales, a network of stations representing at least the main land and vegetation covers (forested vs. open terrain) should be established. Furthermore, several stations at the scale of passive microwave observations (10-25 km radius) would be required for the data to be usable for satellite cal/val purposes.

In summary: The Sodankylä site provides a relatively dense spatio-temporal coverage of snow depth, and soil freeze/thaw observations, which are sufficient to address many user needs in most process and climatological studies specific to the site. Extending the applicability of measured variables beyond local scale requires establishment of more stations covering specific parameters; while efforts have been made to increase the coverage of basic parameters such as snow depth and soil properties (temperature and permittivity profiles), distributed data on parameters such as SWE is lacking.

Recommendations for the in situ Snow scale SWE data collection EU ERA-CLIM2
The data collection was compiled under the EU ERA-CLIM2 project coordinated by ECMWF to serve climate reanalysis. A coordinated effort was made to collect and assess available in situ data on historical snow water equivalent datasets from manual observation networks. While the dataset forms a comprehensive database for use in e.g. climate analyses or climate model evaluations, the database has not been updated beyond the target years of ERA-CLIM2.

Moreover, the basic availability of observations from manually operated networks in the future in uncertain, and there has been little drive to implement replacing networks based on automated sensors.

Recommendations on snow satellite products
The spatial extent of snow cover is typically obtained from optical sensors providing high-to moderate resolution. The associated satellite products are relatively mature, and the spatial resolution of sensors is typically sufficient to meet most user requirements, which range from 0.1 to 5 km even for 'goal' requirements. However, as the observations with optical sensors are typically limited to daylight and cloud free conditions, the available products are typically composites with different levels of temporal aggregation This tradeoff between spatial and temporal coverage forms an impediment in the use of satellite snow extent datasets; e.g. for local NWP temporal resolution requirements (< 12 hours) are typically not met. Furthermore, there is also a degree of inconsistency amongst satellite datasets on snow extent; these were recently assessed in detail in the Satellite Snow Product intercomparison and Evaluation Exercise (SnowPEx; Schwaizer et al., 2016); e.g. for the maximum coverage period in February, different datasets exhibited a range from 30 – 40 % of the Northern Hemisphere land area. As a threshold requirements, an accuracy level of 10-20% is typically needed.
In the case of Snow Water Equivalent, while the temporal resolution of current (daily) products is typically adequate for most user needs, current satellite datasets are generally unable to meet the requirements for product accuracy and spatial resolution. All operational datasets (not including e.g. suborbital lidar observations) are based on passive microwave sensors. The SnowPEx study (Schweizer et al., 2016) assessed the accuracy of different products against in situ dataset on SWE, finding that the RMSE of current best products to be in the range of ~40 mm SWE, which exceeds all user requirements 'threshold' listed in the WMO OSCAR database by a factor of two. Moreover, the satellite products are provided at a spatial resolution of 25 km which in insufficient for most users, in particular in NWP and hydrology which require spatial resolutions from 0.1 km to 05 km as a goal. However, it should be noted that user requirements for SWE are extremely diverse (up to a goal of 100 km for many climate applications)

Walter Oechel (U Exeter)
Recommendations regarding the snow observations in the surrounding of eddy covariance towers
Given the large variability in snow cover conditions across multiple spatial scales, even for sites that are only placed a few hundreds of meters apart significant deviations in snow cover conditions can be present. It is therefore critical to include distributed snow depth measurements within the footprint area of Arctic eddy covariance towers to more accurately capture the temporal and spatial changes of snow cover conditions. These measurements should be performed in locations distant enough from the tower mast to minimize potential disturbance factors, such as e.g. snow drift. The inclusion of these dataset into the eddy covariance data repositories will be particularly valuable for the interpretation of the measured GHG fluxes, given the current complete lack of these measurements.

5.4. Glacier and ice sheet observations

Małgorzata Błaszczyk (USlaski):
Recommendations on measurements of tidewater glacier fronts in Svalbard

Recent years have seen an increase in the availability of velocity data from satellite sources for Svalbard, with varying accuracy and temporal resolution. Svalbard tidewater glaciers are typically slower than the glaciers in Greenland, requiring precise validation of the velocity maps, based on field measurements. Howeverm currently only a few, usually fast flowing and surging glaciers are studied in detail with respect to glacier velocities. Thus, there is a need to validate velocity maps with field data, especially for slower glaciers in Svalbard.
Nowadays, with increasing quantities of satellite data, changes in glaciers' extent are easy accessible. However, proper determination of frontal ablation requires meticulous study of seasonal fluctuations of tidewater glacier fronts. The amplitude of the seasonal oscillations in Svalbard can be significantly larger than their average long-term retreat. Moreover, the minimum extent (maximum retreat) of glaciers in Hornsund occurs in December and January, when glacier calving ceases. Thus, the proper identification of minimal front position during the polar night is especially important for detailed analysis of the tidewater glacier retreat as the answer on climate changes.

Francisco Navarro (UPM)
Recommendations regarding the World Glacier Monitoring Service Fluctuations of Glaciers (FoG) database and related mass balance products.

NOTE: The info that follows is updated as of the Global Glacier Change Bulletin No. 2 (2014-2015) (WGMS, 2017).

Regarding the geographical coverage of surface mass balance (SMB) series for glaciers in the Arctic regions (excluding the Greenland Ice Sheet), there are 3 glacier regions that are not sufficiently covered at present (with "present" we mean here with glaciological SMB measurements for 2014 and 2015, or after 2005 for the geodetic SMB measurements): the Russian Arctic, Greenland Periphery and the Canadian Arctic. The Russian Arctic is by far in the worst situation, with no SMB series, neither glaciological nor geodetic. Greenland Periphery follows, with only 3 glaciological and 1 geodetic SMB series, in spite of its quite large total glacierized area widely distributed over an extensive geographical area. The Canadian Arctic has 4 glaciological and 3 geodetic SMB series, which is not much taking into account its large glacierized area. The rest of Arctic regions (Svalbard and Jan Mayen, Alaska and Iceland) are well covered. Svalbard and Jan Mayen region has no reported (to WGMS) geodetic series, but has 9 glaciological series. Alaska has a huge amount of geodetic SMB measurements (1007).

Though the support of SMB measurement series is not the responsibility of the WGMS, but of the national funding agencies, the WGMS should put all efforts on approaching international organizations such as UNESCO and ICSU so that these organizations ask the national funding agencies to support SMB monitoring programs.

Regarding improvements to the WGMS databases, we suggest that a mechanism is established that allows tracking the changes applied to the various versions of the databases. Under current conditions, if a researcher submits corrections to already available data, these corrections are applied to the database, but the database users would not notice the particular change that has been applied. While recognizing the difficulty of applying a track changes mechanism, we believe that it is a much needed improvement.

Recommendations regarding the World Glacier Monitoring Glacier Thickness Dataset (GlaThiDa)

The GlaThiDa database is lacking a more homogeneous coverage of the various glacier regions of the Arctic. Only the regions where intensive airborne echo-sounding campaigns (e.g. IceBridge Operation) have been performed (Canadian Arctic, Greenland Periphery, and Svalbard and Jan Mayen) have a large set of available data, though in many cases these data are limited to ground-penetrating radar (GPR) profiles along the glacier centerline. For Svalbard, the availability of many echo-sounded glaciers stems from a combination of airborne and ground-based campaigns. Something similar happens with the Russian Arctic, though in this case the number of glaciers with ice-thickness measurements is much lower, though still reasonable. The number of glaciers with ice-thickness measurements reported to the GlaThiDa dataset is very low for both Alaska and Iceland. We note that, in many cases, there are echo-sounded glaciers whose data have not been reported to GlaThiDa, so the GlaThiDa working group should continue to encourage the research groups owning the data to make them available to the wider community (even if this happens after a few years of restricted use by the researchers of the data-collecting institution). Finally, we encourage the people in charge of the IceBridge Operation to collect, in every region, cross-sectional glacier profiles in addition to centerline profiles (we are aware that they do in many cases, but an increase in the share of cross-sectional profiles would be beneficial).

Recommendations regarding the National Snow and Ice Data Center Randolph Glacier Inventory (RGI)
The glacier outlines for all glaciers over the world are available through the RGI. However, they provide just a snapshot in time mostly corresponding to satellite imagery from 1999-2010. Ideally, glacier outlines should be updated regularly (e.g. at a few years interval), but this is unfeasible. Compiling the RGI has been a tremendous effort of many research teams and this cannot be repeated often. However, many glacier outlines do not change that much (e.g. cirque or lateral boundaries of valley glaciers, or ice divides of ice caps); the largest glacier outline changes correspond to the glacier fronts. Consequently it would be convenient to have versions of the RGI issued every e.g. 10 years with (at least) their glacier front positions updated.

Andreas Ahlstrøm (GEUS)
Recommendations regarding the monitoring of the Greenland ice sheet.
To improve our estimates of the current and future contribution of the Greenland ice sheet to sea level rise, we recommend that the three variables pointed out as observation variable gaps in Section 4.1.3 are included on the current PROMICE station network in the ice sheet ablation zone. The variables mentioned were 1) Snow water equivalent (SWE), 2) High-precision elevation and position measurements of automatic stations on the ice sheet surface and 3) Liquid precipitation (rain).

SWE has important applications in surface mass balance calculations and process understanding as it delays and retains meltwater formation and runoff substantially. Including this parameter will help us improve estimates of the Greenland ice sheet contribution to global sea level changes now and in scenarios for the future.

High-precision elevation and position measurements would enable the use of important elevation-dependent meteorological variables in numerical weather prediction, specifically air pressure. Additionally, such data will allow an improved understanding of the interaction between surface meltwater formation and ice flow which allows climate change to affect the ice loss through iceberg calving directly.

Rain measurements would enable us to monitor the important precipitation shift from snow to rain and help us quantify and understand the accelerating effect on meltwater formation and the implications for ice flow. As rain becomes more frequent in the Arctic and on the ice sheet, we can expect an acceleration in the ice sheet mass loss and thus the contribution to global sea level change.

Anne Solgaard (GEUS)
Recommendation regarding the Ice Sheet Surface Velocity Maps

- Better validation of the product using in-situ data (GPS measurements of ice velocity).
- Better documentation of the product and more elaborate meta-data will facilitate the use of the ice velocity product.
- Decrease the time gap between the measurements and the IV production for a closer-to-real time product by automating the work chain.

Shfaqat Abbas Khan (DTU)
Recommendations on Greenland altimetry and ice mass loss measurements.
GNET GPS stations are uplifting in response to past and present-day changes in ice mass. Uplift due to past ice loss, Glacial isostatic adjustment (GIA), is the ongoing response of the solid Earth to ice and ocean load changes occurring since the Last Glacial Maximum (LGM; ~21 thousand years ago). We recommend using Relative sea-level (RSL) observations and geomorphological constraints on historic ice extent to model and remove the GIA signal and isolate the elastic uplift due to present-day ice mass variability.

Though the GNET network is relative dense, there are few spots in West Greenland with only a few stations. Adding a few more stations would improve the spatial resolution of ice-sheet-wide mass loss.

Regarding the improved ice loss product, produced from a combination of GRACE and GNET data, it is recommended to use altimeter-based ice loss maps from CryoSat-2 for validation.

5.5. Geological observations

Peter Voss (GEUS) and Mathilde Sørensen (UiB)
Gaps in the variables required to monitor the seismic activity in the Arctic region.
For the monitoring of the seismic activity in the Arctic region, a lowering of the detection threshold for seismic events will improve hazard determinations. The main challenge is the lack of long term observations on the sea floor. There is also a need for denser observations both onshore as well as offshore, in order to provide accurate information on source mechanisms of seismic events. These requirements must be met to understand and improve the knowledge on natural hazards that target current and future infrastructure.

Recommendations regarding the catalogue on earthquakes and other seismic sources in the Arctic, include:

- Increasing the number of observational sites, especially offshore.
- Keeping analytical resources at a high level at the national and international centres.
- Adoption of real time data exchange on an international level among the nations and researchers that conduct seismological monitoring in the Arctic region.
- Application of improved earthquake location techniques to the Arctic region.

5.6. River discharge observations

David Gustafsson (SMHI)

Recommendations for the in situ river discharge observations provided by the pan-arctic and multi-national Arctic-HYCOS observation system

The Arctic-HYCOS observation system provides in-situ river discharge data from a selection of river discharge gauging stations in the pan-arctic drainage basin of the Arctic Ocean and northern seas (PADB), operated by the National hydrological services (NHS) in Canada, Denmark, Finland, Iceland, Norway, Russian Federation, Sweden, and United States of America. The Global Runoff Data Centre (GRDC) serves as a focal point providing historical data and station metadata, whereas provisional and real-time data should be provided by the NHS. The observation system was assessed with regard to the aims defined by the Arctic-HYCOS project:

- To provide data suitable for evaluating freshwater flux to the Arctic Ocean and northern seas, and
- To provide data suitable to study changes in Arctic hydrological regimes relative to climate change.

The assessment was made using data and metadata available from the Arctic-HYCOS steering committee, as well as openly available data from the web services at GRDC and the NHS. The spatial coverage was assessed in terms of the representation by the observations of the total PADB area as well as the total river discharge to the Arctic Ocean and related northern seas. The drainage basin area and the mean total river discharge to the ocean were estimated using the Arctic-HYPE hydrological model (Andersson et al, 2015; Gelfan et al, 2017). A new version of the model was developed for this purpose, adjusted with information from the Arctic-HYCOS station metadata and discharge data.

The following synthesis/recommendations are made from the analyzed datasets:

a. **Spatial coverage of the Arctic-HYCOS river discharge observation network**
The network includes 427 stations with a subset of 71 'flow-to-ocean' stations including the most downstream stations in each river with station drainage basin area larger than 5000 km^2. 8 additional stations were identified as potential flow-to-ocean stations that could improve the spatial coverage from 52% to 58% of the total PADB, mainly as a consequence of improved spatial coverage in the Russian Federation (from 59% to 69%). The spatial coverage was also high for the North American part of the PADB (around 60%), whereas the coverage is only 15% in Iceland, Scandinavia and Svalbard. Greenland is practically not covered at all. The representation by the Arctic-HYCOS observations of the total river discharge to the ocean (excluding Greenland) was estimated to about 55% and could be further increased to 61% by including the additional 8 flow-to-ocean stations. Flow-to-ocean in Russian rivers is represented to 65% (75%) by the observations and in North American rivers by 54 % (56%) - numbers for the extended flow-to-ocean network in brackets. Overall, the spatial coverage can be considered very good with regard to drainage area and flow-to-ocean. The actual numbers (around 60%) is somewhat below the tentative requirement of 75%. The low spatial coverage in Scandinavia and Iceland is partly due to the limitation to drainage basins >5000 km^2. The low spatial coverage on Greenland is not critical, given that the fresh-water flux from Greenland is estimated through an enhanced dataset developed by GEUS in the INTAROS project. The main recommendation to the Arctic-HYCOS

project is thus to re-consider the list of flow-to-ocean stations to improve the spatial coverage as much as possible with stations available in the existing national networks.

b. **Temporal coverage and timeliness of the Arctic-HYCOS river discharge observations**
The length of the Arctic-HYCOS river discharge time-series are on average around 50 years, which is well above the tentative requirement of more than 30 years for studies of hydrological change in relation to climate. The longest time series from each country extends more than 100 years. However, the timeliness of historical data sets to be updated at the GRDC Arctic-HYCOS archive varies considerably between the countries; at best, data are updated within 2 years from observations. The access to real-time observations with timeliness of 1 day is only available from the USA, Canada, Finland, and Norway. This update frequency is acceptable for climate change analyses and model development and validation, but it is highly recommended to improve the timeliness and availability of provisional and real-time data for more real-time analyses and forecast applications.

c. **Metadata, supporting measured variables, uncertainty, and documentation of the Arctic-HYCOS river discharge observations**
The current Arctic-HYCOS network includes 427 stations. GRDC identifiers necessary to access the time-series data from the GRDC repositories are provided only for 353 of these 427 stations. Additionally 40 stations (in total 393) could be linked to the GRDC repositories using national stations identifiers and/or station location and upstream area. Additional data from NHS repositories was still needed to complete the time series data. The Arctic-HYCOS station list and metadata is still under development and a finalized and completed data set is expected to be published at GRDC during 2018.

There is currently no uncertainty characterization included in the metadata. The intention of the Arctic-HYCOS project is to provide a simplified qualitative uncertainty index, indicating issues such as under-ice conditions and updates of rating curve parameters.

There is no supporting documentation of measurement instrumentation, processing procedures, or validation reports provided by GRDC. Users of the data are dependent on documentation provided by the NHS, which is sometimes excellent but more often limited or non-existing. A recommendation to the Arctic-HYCOS project is thus to improve the availability of such supporting documentation both at the GRDC Arctic-HYCOS web service and at the web services of the NHS.

The river discharge data are derived from water level measurements using so-called rating curves established for the station river cross-section through simultaneous water level and discharge observations. The usability of the Arctic-HYCOS discharge data would be largely improved if the water level measurements were made available along with the derived discharge data, especially in light of the recently improved possibility to obtain inland water levels by satellite altimetry.

In summary: The Arctic-HYCOS observation system provides long-term data sets of river discharge with very good spatial and temporal coverage over large parts of the Arctic domain, which are suitable for studies of hydrological change in relation to climate change and estimation of river freshwater inflow to the Arctic Ocean and related northern seas. The observation system can be improved through improved timeliness of the data, improved metadata including uncertainty characterization and supporting documentation, as well as publication of additional data such as the original water level measurements.

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INTAROS

This report is made under the project
Integrated Arctic Observation System (INTAROS)
funded by the European Commission Horizon 2020 program
Grant Agreement no. 727890.

Project partners: