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Deliverable 2.4

Report on present observing capacities and gaps: Atmosphere

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EXECUTIVE SUMMARY

This document includes the description and assessment of atmospheric in situ observing systems, data collections and satellite products. On the basis of the assessment, critical knowledge gaps are identified and recommendations to solve them are provided. This document is intended to:

- define the current gaps in knowledge in atmospheric fields that are critical for operational weather forecasts, and for the understanding of processes that need to be better represented in climate models.
- suggest where the focus in future Arctic atmospheric observations should be.

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1. Introduction

This report is prepared to assess the existing atmosphere 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 atmosphere 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, there is one in situ global atmospheric/surface network with stations also in the Arctic (Baseline Surface Radiation Network (BSRN)) and satellite atmospheric/surface products such as the ESA-CCI Aerosol datasets, the Heleosat Surface Radiation (from MVIRI instruments onboard the geostationary Meteosat satellites), the CLARA-A1 Surface Radiation (Advanced Very High Resolution Radiometer (AVHRR) on the NOAA satellite series), and the CLARA-A1 Cloud Properties that have global coverage and, therefore, cover the Arctic.

Concerning other satellite data, selected atmospheric products such as precipitation, atmospheric gases, wind speed over the surface, and cloud top height, were addressed in the Polar View report on Gaps and Impact Analysis of the existing EO missions in Polar Regions (Polar View, 2016). However, the focus of the gap analysis was on cryospheric products, without explicit conclusions on the gaps in atmospheric products.

In situ atmospheric observation networks were evaluated in the framework of the H2020 project GAIA-CLIM using the SMM approach developed in CORE-CLIMAX adapted to in situ measurement series (Thorne et al., 2017). Many of the addressed networks partly cover the Arctic region, and are composed of stations whose data have rather heterogeneous characteristics (in terms of data quality, temporal length of data records, data management). Hence, the results of the assessment do not necessarily reflect the specific characteristics of the Arctic portion of the addressed networks.

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 atmospheric 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, and with respect to 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 are 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.

There are many types of observing systems, reflecting a large variety in technical solutions and different maturity and organizational levels of the in situ measurements. For the atmosphere there are several mature observing systems, such as international networks, that follow standardized data managements. In the marine sphere observations are more diversified and fragmented, providing more types of data with various degree of standardization. The marine observing systems are usually identified on the basis of the utilized platforms (moorings, floats, gliders,…), in line with the classification of global observing systems made in the GCOS 2016 Implementation Plan (GCOS, 2016).

The different atmosphere 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 collections are created from the merging of data produced by different observing systems.

We address different kind of data collections:
1) data from established atmosphere 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-, UAV-based), 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 Questionnaire B.

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), 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 atmosphere observing systems are not included such as some of the supersites belonging to the International Arctic Systems for Observing the Atmosphere (IASOA). 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 incorporated in 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 the ESA's Climate Change Initiative (CCI) projects for various atmospheric variables. 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 addressed in situ observing systems, in situ data collections, and satellite products, and the work done to characterize them (determining coverage, resolution, uncertainty, etc.) in order to allow their thorough assessment.

2.1 UiB

2.1.1 Stable water isotopes

Stable isotopes in water vapor and precipitation are a natural tracer containing time integrated information about processes in the atmospheric water cycle. This kind of information is highly relevant for constraining the water cycle in numerical models of the atmosphere. Recent availability of in-situ spectroscopy allows for acquiring this observation at high temporal resolution and coverage. Organized measurement activity is still in early stages and evolving from bottom-up measurement networks and isolated field observations.

Stable isotope ratios of oxygen ($^{18}O/^{16}O$ and $^{17}O/^{16}O$) and hydrogen (D/H), expressed in relation to a standard as $\delta^{18}O$, $\delta^{17}O$ and δD, are an important tracer for the evaporation and transport conditions of moisture within the atmospheric hydrological cycle (Jouzel et al. 1997). The stable isotope composition of water vapor reflects the Lagrangian-integrated evaporation, transport and condensation history of an airmass (Sodemann et al. 2008). As the heavier stable isotopes prefer the more tightly bound phase, isotopic equilibrium fractionation allows interpretation of δD and $\delta^{18}O$ as tracers for air-mass cold points, allowing for example to separate different airmasses across fronts (Aemisegger et al. 2015). In addition, the derived stable isotope parameters Deuterium excess (d-excess = $\delta D - 8 \cdot \delta^{18}O$; Dansgaard 1964) and, more recently, the ^{17}O-excess (Barkan and Luz 2007) are influenced by non-equilibrium fractionation, and thus carry a signal on the evaporation conditions at the moisture sources (Merlivat and Jouzel 1979; Pfahl and Sodemann 2014; Landais et al. 2012). Precipitation preserves the isotope signature in the cloud to various degrees. Measuring stable isotopes at the evaporation source, during vapour transport, and in precipitation enable ways to constrain the water cycle in models.

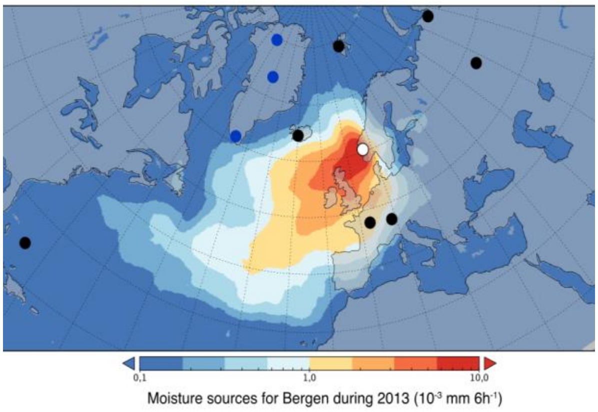


Figure 1. Currently active (black, white dots) and previous (blue dots) water vapour isotope measurement in the AC-AHC Network of Stations. Shading shows moisture source climatology for Bergen in 2013 to illustrate relation between stations in the network (10-3 mm 6h-1).

Within the project AC-AHC2 (Atmospheric circulation and Arctic hydrological cycle changes), data between Network stations (including Bergen) and the continuous stable isotope measurements on board of R/V Polarstern are shared. Some first results from individual sites have been reported (Steen-Larsen et al. 2015; Bonne et al. 2015; Bastrikov et al. 2014) but data from the entire network have not yet been used to reveal coherent signatures of weather events across larger spatial scales (Fig. 1). During the Year of Polar Prediction Special Observations Period 1 (March 2018), airborne and ship-based vapour isotope measurements are performed in the Iceland Sea region. Ship-based isotope observations will be performed in the Fram Strait later in 2018. This makes the European Arctic the region with the densest coverage of stable isotope observations worldwide. Further airborne measurements will be done in the same region during the ERC CoG project ISLAS within the next 3-5 years.

An important, but yet hardly addressed, question is the temporal and spatial representativeness of stable water isotope measurements at the individual sites. In extreme cases, the d-excess carries an evaporation signature over 15° latitude (Bonne et al. 2015), while local boundary-layer dynamics determine a large part of the diurnal variability elsewhere (Noone et al. 2011). Particularly in complex terrain, even small-scale precipitation and evaporation processes can affect stable isotopes in precipitation. Consideration of these aspects is key to an accurate interpretation of the moisture transport history conveyed through stable isotopes.

2.2 IMR

2.2.1 IMR-PINRO Ecosystem Survey

This survey covers the Barents Sea (Norwegian, Russian and international sectors), while in more recent years, with less sea ice, the area north of West-Spitsbergen has also been included (Figs. 2a & 2b). The extent is roughly 68-82° N and 5-60° E. The Ecosystem Survey as such has been run annually in August-September 2004. It is an expansion of earlier IMR surveys, in particular the 0-group survey established in 1965**.**

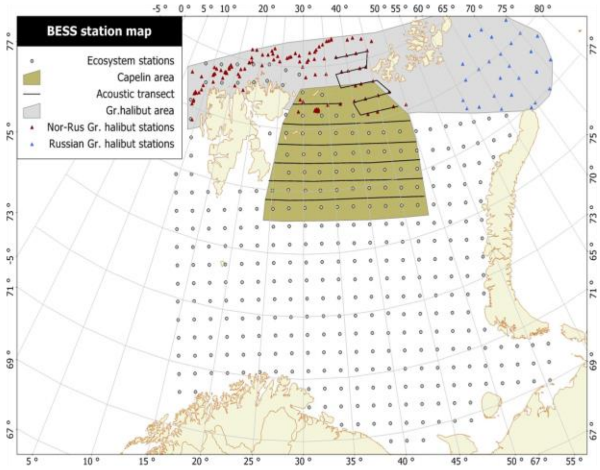


Figure 2a. Map of the standard Barents Sea Ecosystem Survey.

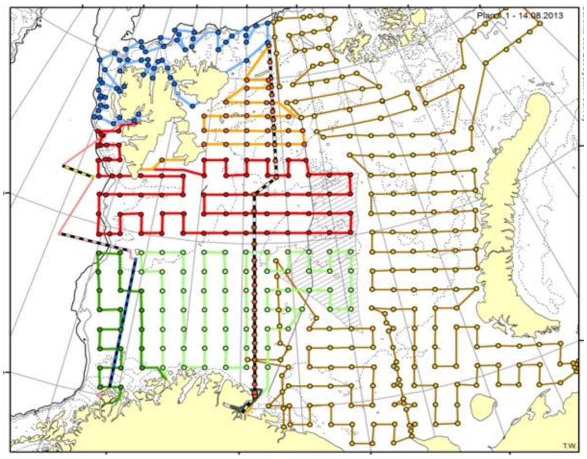


Figure 2b. Cruise lines for the IMR-PINRO Ecosystem Survey August-September 2013. Different colors indicate different vessels.

The survey is based on in-situ measurements from scientific vessels (normally three) and provides a broad range of interdisciplinary observations, while making these available towards advice to fisheries management and various applied and more basic research projects (Eriksen et al. 2013 and in press). IMR and PINRO make sure that the survey is conducted in the technically and scientifically best possible manner. Research and development is undertaken to ensure that the vessels and equipment are based on state of the art technology and are continuously upgraded.

Numerous instruments and other types of equipment are used, for example bottom trawls. For the propose of this deliverable we consider only the ship-borne basic meteorological observations, taken continuously during the surveys. The data are stored in a national repository according to legal constraints on their location and is handled by the Norwegian Marine Data Centre, Bergen, Norway. Most data are also shared with and stored at the International Council for Exploration of the Sea (ICES) in Copenhagen, Denmark.

2.2.2 Barents Sea winter study

This survey covers the Barents Sea (Norwegian, Russian and international sectors) and is performed annually in January-February since 1976. The extent is roughly68-80°N, 7-56 °E; see Figs. 3 and 4.

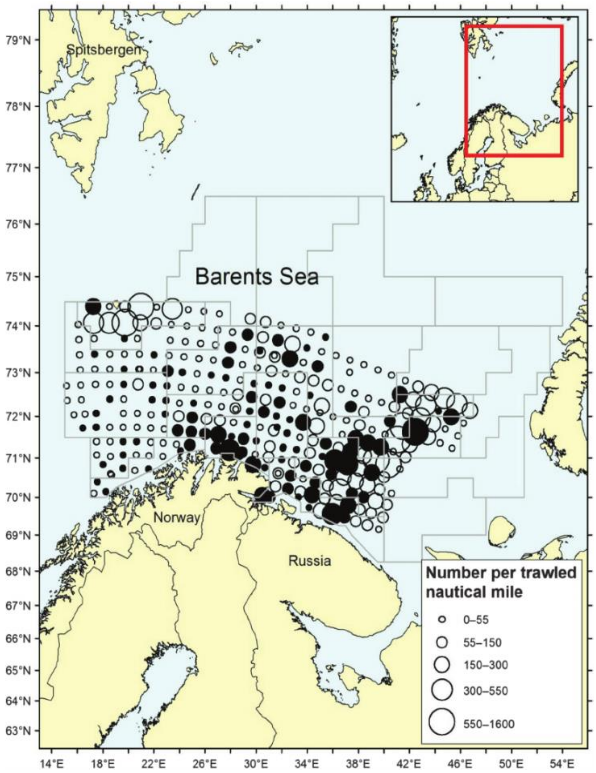


Figure 3. Catch (in numbers) of cod per nautical mile trawled during the joint Russian–Norwegian winter 1991 Barents Sea survey. Main areas used for swept area estimations and acoustic estimations at the time are shown. The coverage has now been expanded.

Figure 4. Norwegian research vessel "G.O. Sars" designed for multipurpose surveys and build in 2004.

The survey is based on in-situ measurements from scientific vessels. It provides a range of interdisciplinary observations, making these available mainly towards advice to fisheries management and various applied research projects. It is less broad than Barents Sea Ecosystem Survey and more focused on the main commercially harvested fish stocks. For the purpose o this deliverable we only consider the basic meteorological observations carried out on the research vessel. Further details are given in Mehl et al. (2016).

Data are stored in a national repository according to legal constraints on their location. The data are handled by the Norwegian Marine Data Centre, Bergen, Norway. Most data are also shared with and stored at the International Council for Exploration of the Sea (ICES) in Copenhagen, Denmark. Records are regularly and frequently updated with new observations. Data is available on supervised request through originator.

2.3 MISU

2.3.1 Evaluating thermodynamic structure from AIRS satellite information

This evaluation focuses on thermodynamic profiles from the Atmospheric Infrared Sounder (AIRS) hyperspectral infrared sounder instrument (Chahine et al. 2006) flying onboard the Aqua satellite since its launch in mid-2002 (Parkinson 2003). AIRS thermodynamics across the Arctic have been exploited in a variety of scientific studies (Devasthale et al. 2010, 2011, 2013, 2016; Sedlar and Devasthale 2012; Boisvert et al. 2013, 2015; Boisvert and Stroeve 2015; Sedlar and Tjernström 2017). A thorough evaluation of AIRS thermodynamic profiles over the high-latitude Arctic is, however, missing in the literature. Profiles of atmospheric temperature (T) and water vapor mixing ratio (Q) from the Atmospheric Infrared Sounder (AIRS, Chahine et al., 2006) satellite are here evaluated against radiosounding profile measurements across the pan-Arctic region. More details can be found in Appendix A2.3.

The spatial distribution of radiosounding releases here used to evaluate AIRS thermodynamics are shown in Fig. 5. Three pan-Arctic observatories, at Barrow (Alaska), Tiksi (Russia) and Ny-Ålesund (Svalbard) are included along with the cruise tracks of four intensive field campaigns in Fig. 5a. The land-based observatories regularly operate daily to twice-daily radiosounding releases. The intensive field campaigns (ASCOS: Tjernström et al. 2015; ACSE: Sotiropoulou 2016; N-ICE: Granskog et al. 2018; Sea State: Thompson 2015; Polarstern Driemel et al. 2016) nominally launched radiosoundings every 6 hours, except for N-ICE that released soundings twice-daily. Fig. 5b shows the individual radiosounding release locations from intensive field campaigns onboard the Polarstern research vessel. The combined distribution of these radiosounding releases sufficiently covers much of the Arctic Ocean domain. Furthermore, the selection of the land-based stations capture atmospheric influences across 3 main geographic regions: the North Atlantic (Ny-Ålesund), the Siberian continent (Tiksi), and the North Pacific (Barrow). Table A1 describes the timeline of operation and the sounding frequency for each of the observatories.

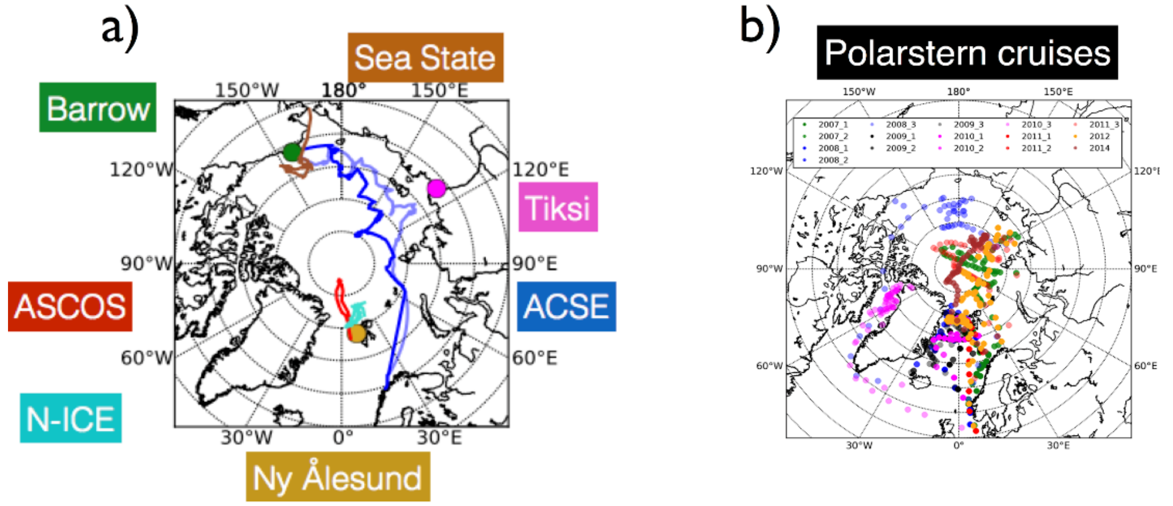


Figure 5. a) Pan-Arctic land based radiosounding stations and cruise track coverage from 4 intensive observations campaigns. b) Individual sounding release locations from 7 selected intensive field campaigns onboard the German research vessel Polarstern.

The focus period for this study is January 2003 to August 2016 for AIRS-radiosounding comparisons. All the land-based pan-Arctic observatories operated radiosounding releases continuously from the same location during this period. These observatories provide an exceptional reference to AIRS thermodynamics over the full Arctic annual cycle. The intensive field campaigns add thermodynamic profile information over the sparsely observed central Arctic Ocean sea ice. Except for N-ICE, all the field campaigns were operational during Arctic summer and autumn (Table A1).

A brief description of the method employed to compare AIRS Level 3 (L3) with radiosounding thermodynamics is presented. AIRS (L3) profiles are gridded data at 1°x1° resolution, reported twice daily for the ascending and descending polar orbiting direction, respectively, valid at approximately 13:30 (ascending) and 01:30 (descending) local time each day. AIRS observes infrared radiances at 2378 infrared channels covering wavelengths from 3.7 to 15.4 µm. These radiances are converted to brightness temperatures that probe the atmospheric column vertically along varying wavelength channels. Vertical weighting kernels are used to convert the brightness temperatures to physical profiles of T and Q (e.g. Chahine et al. 2006). Stated accuracies for the thermodynamic retrievals are relatively robust, at 1 K per km for T, and 15% per 2 km for Q (http://airs.jpl.nasa.gov/data/product_accuracies/).

Gridded ascending and descending overpasses for each day are averaged, resulting in AIRS mean profiles of T and Q. AIRS L3 thermodynamics are retrieved on standard pressure levels across the troposphere. In this study, the following pressure levels are analyzed: 1000, 925, 850, 700, 600, 500, 400 and 300 hPa. We analyzed the pressure-level data, whereas the values are valid for a particular pressure level and are not layer-averaged quantities.

All radiosoundings from the observatories are first converted from Coordinated Universal Time (UTC) to local time, based on the longitudinal location of sounding launch. Available sounding profiles within one day are then averaged to produce daily mean profiles of T and Q. The vertical resolution of radiosounding thermodynamics is far superior in comparison to AIRS L3 standard pressure levels. To obtain sounding profiles on the same standard pressure levels as AIRS, a cubic interpolation between reported sounding pressure levels is used.

To compare with daily averaged radiosounding T and Q profiles, the nearest AIRS L3 grid box to the sounding release coordinates is found. AIRS L3 daily averaged T and Q profiles are then compared statistically with the radiosoundings as reference. In this analysis, an evaluation of AIRS T and Q profiles are first examined seasonally with respect to Barrow radiosoundings. Then an evaluation of the other observatories is performed using the results from Barrow as a baseline to evaluate the strengths and weaknesses of AIRS thermodynamics across the Arctic. In Appendix 2.3, we expand upon the evaluation to further highlight the applicability of AIRS thermodynamics over the Arctic, with a focus on inter-related thermodynamic processes.

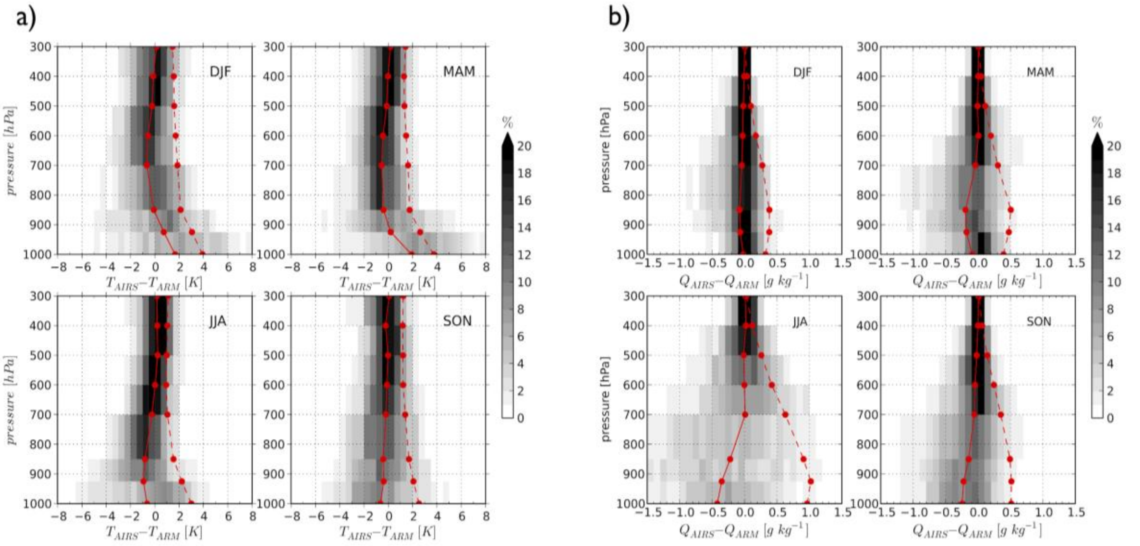


Figure 6. Seasonal (DJF, MAM, JJA, SON) difference distribution frequency [contours, %] of a) T and b) Q as a function of pressure level for AIRS minus Barrow (ARM) daily mean radiosoundings, 2003-2016. MBE (solid red) and RMSE (dashed red) profiles overlaid on distribution frequencies.

Relative frequency distributions (RFDs) of the seasonal difference in T (Fig. 6a) and Q (Fig. 6b) and the associated mean bias errors (MBEs) and root mean square errors (RMSEs) illustrate seasonal trends. AIRS T and Q profiles consistently have the smallest MBE and RMSE ranges above 600 hPa regardless of season; the largest deviations from radiosoundings occurs below this altitude. The distributions indicate an increasing spread in T and Q differences from soundings, and corresponding increases in MBE and RMSE, with decreasing altitude. During DJF and MAM, AIRS has relatively large warm, and slightly dry, biases across the lower troposphere. By JJA and SON, the T bias reveals a modest cold bias and an enhanced dry bias that extends across a deeper layer through the lower troposphere; the distribution spread of Q during JJA is exceptionally large and is reflected in RMSE ranging from 0.5-1.0 g kg^{-1} (Fig.

6b). Below 600 hPa, RMSE for *T* is the largest during the winter and spring seasons; for *Q*, the RMSE in the lower troposphere are instead largest during summer and autumn seasons. See Appendix A2.3 for distribution differences from the other observatories in Fig. 5.

Seasonal profiles of MBE and RMSE from all 3 land-based observatories and combining all central Arctic field campaigns are shown in Fig. 7. Similar to the analysis for Barrow, *T* and *Q* RMSE increases with increasing pressure. Seasonally, a warm bias in AIRS T is present at all observatories during winter and spring (Fig. 7a); the warm bias is generally not confined below 850 hPa at Ny-Ålesund as it is at for Barrow and Tiksi. Similarly, a cold bias in the lower troposphere *T* is found for all observatories during summer and autumn. The AIRS cold *T* bias at Tiksi and Ny-Ålesund during JJA is over 3 times larger than at Barrow and from the field campaigns; MBE in AIRS *Q* for the former 2 stations was also roughly 2 times larger than the latter 2 stations. However, Ny-Ålesund was the only observatory with a lower tropospheric positive MBE in *Q* during DJF and SON (Fig. 7b); the largest during DJF and corresponded with positive MBE in *T*, while the MBE in *T* during SON was negative.

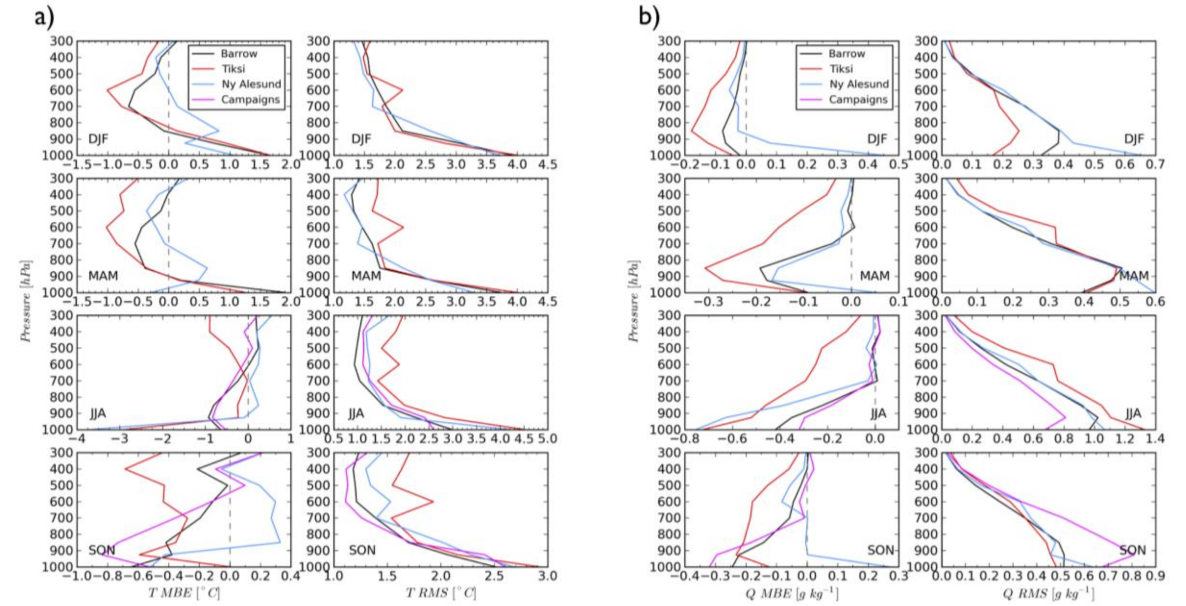


Figure 7. Seasonal MBE and RMSE profiles as function of pressure level [hPa] in a) T [°C] and b) Q [g kg^{-1}] for all AIRS-radiosounding comparisons: Barrow (black), Tiksi (red), Ny-Ålesund (blue) and all central Arctic field campaigns combined (magenta). Profiles for central Arctic field campaigns are only shown for JJA and SON, when the campaigns operated.

Combining monthly *T* and *Q* observations from all observatories, the relative error in monthly AIRS thermodynamics relative to radiosoundings for the lowermost 4 pressure levels is shown in Fig. 8; here we focus on the lower troposphere where the analysis from Figs. 6 and 7 reveal the largest errors and distribution spread in AIRS values.

With respect to monthly consistency of relative error distributions within a season, *T* errors during DJF and JJA are the most similar across the lower troposphere. The relative errors in *T* for these seasons tend to increase from 700 hPa to 1000 hPa in a similar intraseasonal manner; during winter relative errors increase from below 20% at 700 hPa to below 40% nearest the surface with distinct distribution maxima below 10 to 15% (Fig. 8, 1st column). By summer, *T* relative errors increase from 40% at 700 hPa to as large as 100% at 1000 hPa with a relatively flat distribution (Fig. 8, 3rd column). Intraseasonal inconsistency in the monthly error distributions of *T* within the lower troposphere is present during the spring and autumn shoulder seasons (Fig. 8, 2nd & 4th columns). In particular, error distributions of *T* in March and September resemble the previous winter and summer seasons, respectively, especially moving through the atmosphere towards the surface. Oppositely, *T* error distributions for May and November are more consistent with their respective subsequent season.

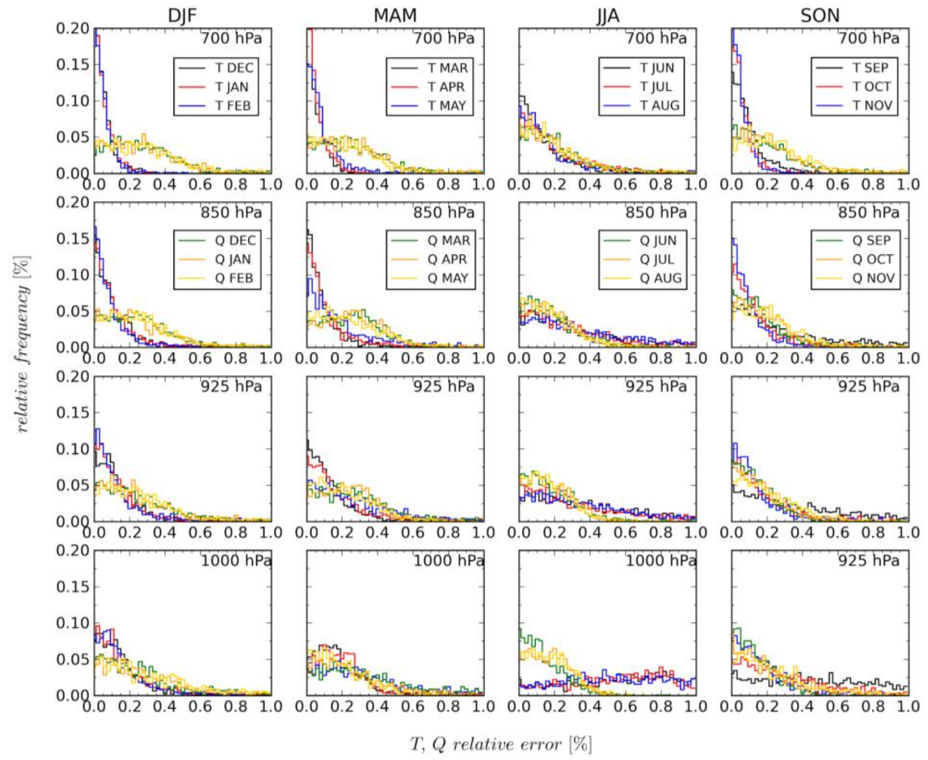


Figure 8. Relative error frequency distributions, defined as (AIRS - Sounding)/Sounding [%], in monthly T (black, red, blue) and Q (green, orange, yellow) for the 4 lowermost AIRS pressure levels (top to bottom: 700, 850, 925, 1000 hPa). Columns are grouped seasonally, from left to right, as DJF, MAM, JJA, and SON.

Interestingly, relative errors in *Q* are consistent for all seasons, generally below 50% with relative error distribution peaks often ranging between 0 and 30%. Even during JJA when relative errors in *T* below 850 hPa span a large range, the relative error range in *Q* is confined at approximately half that of *T*. This is likely caused by two factors: 1) *Q* over the Arctic region is generally limited to a relatively small range between 0 to 15 g kg^{-1}, making it difficult for the in-situ radiosounding observation to differ dramatically from the *Q* retrieval from AIRS; 2) the water vapor mixing ratio dependence on temperature. Water vapor is constrained by the saturation level due to Clausius-Clapeyron, while atmospheric temperatures are free to exhibit larger fluctuations; only when moisture is transported horizontally or vertically from the surface will it covary with the temperature distribution. The consumption of water vapor into condensed cloud water may further contribute to the reduction in relative error distribution of *Q* by reducing its observed range.

To begin to understand the biases found in AIRS daily averaged L3 thermodynamics, we examine AIRS ascending and descending thermodynamic profiles together with ASCOS radiosoundings over the central Arctic sea ice at 87.5°N on 27 August 2008. Fig. 9 shows the 00:00 and 12:00 UTC (blue and red; same as local time) radiosoundings and displays a significant amount of fine-scale vertical structure and temporal variability. This variability in T is most pronounced in the lower troposphere (Fig. 9a), while in Q, the variability is mostly found at levels above 850 hPa (Fig. 9b). The daily averaged sounding thermodynamics at the AIRS pressure levels (green) end up in between; however, the daily averaged T profile still resolves the decrease in T from 1000 to 925 hPa, as well as a temperature inversion structure between 925 and 850 hPa, which is associated with a low level cloud with cloud top levels at 00 and 12 UTC depicted by dashed lines. The corresponding AIRS profiles at 01:30 (descending) and 13:30 (ascending) UTC fail to capture this important lower tropospheric thermodynamic structure. Both ascending and descending T profiles show an increasing, stable structure below 925 hPa and thus fail to capture the in-situ observed elevated temperature inversion structure (Fig. 9a). Instead they indicate a surfaced based inversion which leads to a misrepresentation of the stability of the lower troposphere. Water vapor below the cloud top levels are biased low, but recover in the free troposphere above the cloud top (Fig. 9b).
The cloudy boundary layer structure observed by radiosoundings in this example are commonly observed over the summer and autumn Arctic sea ice (Sedlar et al. 2011, 2012; Shupe 2011; Shupe et al. 2013; Sedlar 2014; Sotiropoulou et al. 2014). Relatively large MBE and RMSE in AIRS thermodynamics below ~ 700 hPa, shown in Figs. 6-8 above, are likely exacerbated by the complex thermodynamic structure and influence of low-level clouds on AIRS retrievals. The limited vertical resolution of AIRS further contributes to biases in the low-level thermodynamic structure.

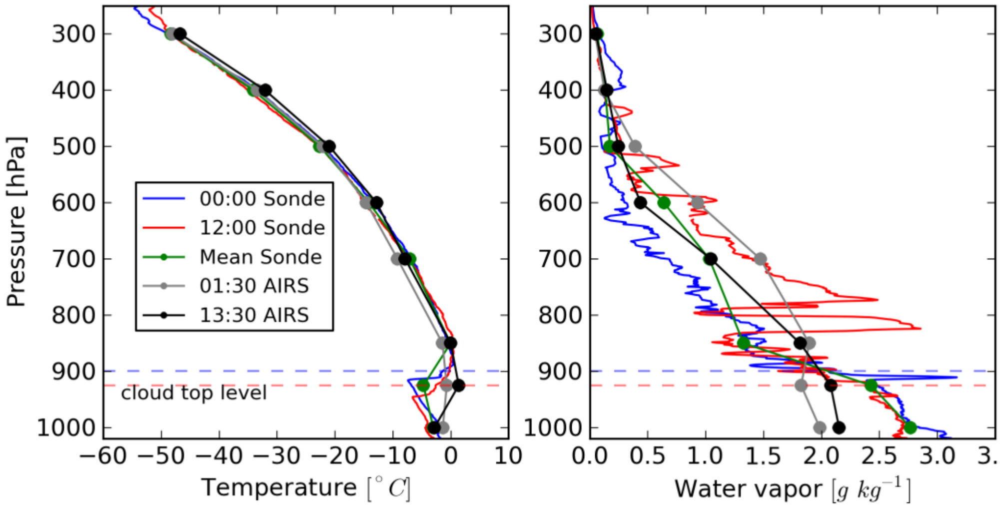


Figure 9. Sounding and AIRS a) (left) temperature [°C] and b) (right) water vapor mixing ratio [g kg^{-1}] profiles on 27 August 2008 at 87.5°N, 8.4°W from ASCOS. Native resolution soundings at 00:00 (blue) and 12:00 (red) UTC and the daily average (green) are shown along with AIRS descending (01:30 UTC, gray) and ascending (13:30 UTC, black) profiles. Dashed horizontal lines indicate the cloud top level at 00:00 (blue) and 12:00 (red) UTC, respectively.

2.3.2 Atmospheric observations from central Arctic field campaigns

This section includes a brief description of the atmospheric observations from the intensive Arctic field campaigns (ASCOS: Tjernström et al. 2015; ACSE: Sotiropoulou 2016; N-ICE: Granskog et al. 2018; Sea State: Thompson 2015; Polarstern: Driemel et al. 2016). The operating locations of the field campaigns are shown in Fig. 5; dates of operation for each campaign are provided in the Appendix Table A1. Each field campaign was organized with a specific research theme and therefore do not provide the same data products; here we describe the data product and the instrument(s) providing the necessary measurements.

2.3.2.1 Radiosounding temperature, water vapor and winds (all field campaigns)

A central measurement operated during all field campaigns analyzed here include regular radiosounding releases. These measurements provide detailed profiles of temperature, relative humidity, wind speed, wind direction, pressure and height. During ASCOS, ASCE and Sea State, soundings were released 4 times daily and intermittently more frequently. Polarstern and N-ICE released 1-2 soundings per day.

2.3.2.2 Cloud properties (ASCOS, ACSE)

Extensive surface-based remote-sensing instrumentation of cloud properties was deployed during both ASCOS and ACSE. This suite of remote sensors included zenith-viewing K_a-band and W-band cloud Doppler radars, Doppler and ceilometer backscatter lidars, and dual-channel microwave radiometers (MWR). The dual-channel MWR measure atmospheric brightness temperatures at 2 microwave frequencies sensitive to atmospheric water vapor and cloud liquid water burden (Westwater et al. 2005; Cadeddu et al. 2013). The instrument retrieval translates these brightness temperatures to integrated atmospheric quantities. They provide a measure of the cloud liquid water path and total column water vapor. Typically, these measurements are retrieved every 15 to 20 seconds.

A time-height resolved cloud mask (zenith cloud fraction, cloud boundaries) is produced by combining measurement streams from the zenith-viewing cloud radar, the lidar instruments and the MWR, aided by temperature and moisture profiles from soundings. The cloud radar is designed to observe the cross-sectional reflectivity of cloud and precipitation hydrometeors across a vertical range gate resolution of 30-45 m. The radar is sensitive to hydrometeor size, and the backscattered reflectivity is dominated by larger cloud particles, typically ice crystals and solid and liquid precipitation. When precipitation occurs, the radar reflectivity signal is attenuated by the falling hydrometeors and can mask individual cloud layers. Lidars operate at visible wavelengths and are thus very sensitive to small liquid hydrometeors. Combining these instrument streams typically yields a robust mask of the lowest cloud base and highest cloud top height, but frequent multiple cloud layers have been identified using these instruments. The typical temporal resolution of the cloud mask is 15-20 seconds.

Vertical profiles of ice water content (IWC) are derived using the methodology of Shupe (2007). The retrieval combines data streams from the cloud radar, lidar, MWR and thermodynamic profiles from radiosoundings to produce a time-height resolved cloud classification data record. Radar reflectivity in the vertical layers where cloud ice is classified are used to derive the profile of IWC using established power law relationships (c.f., Shupe et al. 2004). The typical IWC temporal resolution is 1 minute.

2.3.2.3 Near-surface radiation budget (ASCOS, ACSE, N-ICE, Sea State)

Near surface radiation measurements were routinely made during all field campaigns except the Polarstern cruises. Radiation is measured by deploying broadband radiometers on the sea ice or onboard the research vessel. Radiometers deployed onboard the vessels are generally limited to only observing the downwelling shortwave and longwave radiation; upwelling fluxes are contaminated by the research vessel. This is the case for radiation measurements during ACSE and Sea State, although upwelling radiation can be estimated using albedo estimates for shortwave and surface temperature for longwave radiation. During both ASCOS and N-ICE, the radiometers were deployed on an ice floe, and measured both the upwelling and downwelling (net) components of longwave and shortwave radiation at approximately 1 m above the ice surface. Radiation measurements are typically measured at 1 Hz but typically presented averaged over minutes.

2.3.2.4 Near-surface turbulent fluxes (ASCOS, ACSE, N-ICE, Sea State)

When sensible and latent heat fluxes are available together with near-surface radiation, as was the case in all field data except that from Polarstern, it covers all components of the surface energy budget except conduction through the ice. Additionally, the flux of momentum to the ice is available. These measurements are typically derived using one of two methodologies: 1) high frequency temperature, moisture and 3D winds are combined using eddy covariance; or 2) bulk estimates of vertical turbulent fluxes using measured gradients and turbulent exchange coefficients. Turbulent fluxes are generally averaged over a period of 10-20 min to capture all the relevant scales of eddies representing the turbulent flow.

2.4 AU

2.4.1 Greenland Ecosystem Monitoring Programme

The Greenland Ecosystem Monitoring Program (GEM) was established in 1994 with the aim of quantifying climate change and ecosystem responses (e.g. Table 1) in Greenland. The programme now includes 5 sub-programmes responsible for monitoring of atmosphere, terrestrial, marine, limnic and glacial systems with focus on two sites; a high Arctic site in East Greenland (74°N), and a sub-arctic site near Nuuk, West Greenland (64°N) (Fig. 10).

Table 1. Example of CO_2 flux measurements, expressed as Net Ecosysetm Exchange from Zackenberg, East Greenland

Year	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Measurements start	28 May	27 May	30 Mar	16 May	5 May	3 May	26 Apr	1 May	20 Apr	11 Jul
Measurements end	27 Aug	28 Oct	28 Oct	22 Oct	31 Oct	16 Aug	29 Oct	26 Oct	18 Oct	18 Oct
Start of net uptake period	8 Jul	16 Jun	6 Jul	13 Jun	1 Jul	26 Jun	11 Jul	14 Jun	16 Jul	11 Jul
End of net uptake period	23 Aug	19 Aug	20 Aug	15 Aug	14 Aug	15 Aug	22 Aug	6 Aug	19 Aug	28 Aug
NEE for measuring period (g C m^{-2})	−24.9	−28.2	−11.2	−11.1	5.0	−23.0	−4.6	−0.7	4.8	0.9
NEE for net uptake period (g C m^{-2})	−28.9	−37.8	−32.0	−23.1	−26.8	−31.5	−28.9	−26.8	−17.7	−13.6
Max. daily accumulation (g C m^{-2} d^{-1})	−1.11	−1.32	−1.30	−0.97	−1.14	−0.97	−1.11	−1.14	−1.01	−0.89

The ClimateBasis programme monitors climate and hydrology at the two sites and is run by *Asiaq - Greenland Survey*. The collected data build base-line information on climate variability and trends for all the other sub-programmes within GEM and serve as a trustworthy foundation for adaptation strategies for the Greenlandic society. The stations are embedded in Asiaq's extensive climate and hydrology monitoring network. Furthermore, the run-off data is delivered to the *World Hydrological Cycle Observing System* (WHYCOS) and the *Global Runoff Data Centre* (GRDC) networks.

Atmospheric parameters are collected redundantly at each location on two separated masts with individual power supply in order to be able to treat data gaps and sensor biases consistently. Hydrometric parameters are monitored on various automated stations. A challenging focus is put on the establishment of reliable stage-discharge relations whose temporal stability depends on the river bed. At the river Zackenberg for instance, repeated glacier outburst floods require an updated stage-discharge relation every year, where the related field work is performed together with the GeoBasis sub-programme. Glaciological measurements (surface mass and energy balance, ice flow) complement the monitoring activities in Kobbefjord on a small mountain glacier and two fully equipped energy balance stations (one in Upernaviarsuk in South Greenland, one in Qaanaq in North Greenland) have been added to the sub-programme after 2012. Finally plot and landscape scale flux measurements of CO_2, CH_4, H_2O and energy in wet and dry ecosystems are conducted.

Although the GEM programme is extensive and includes coordinated monitoring across biomes and habitats, two major challenges has been identified; the improved integration of remote sensing products and improved tools for up-scaling the findings from the monitoring sites to larger parts of Greenland

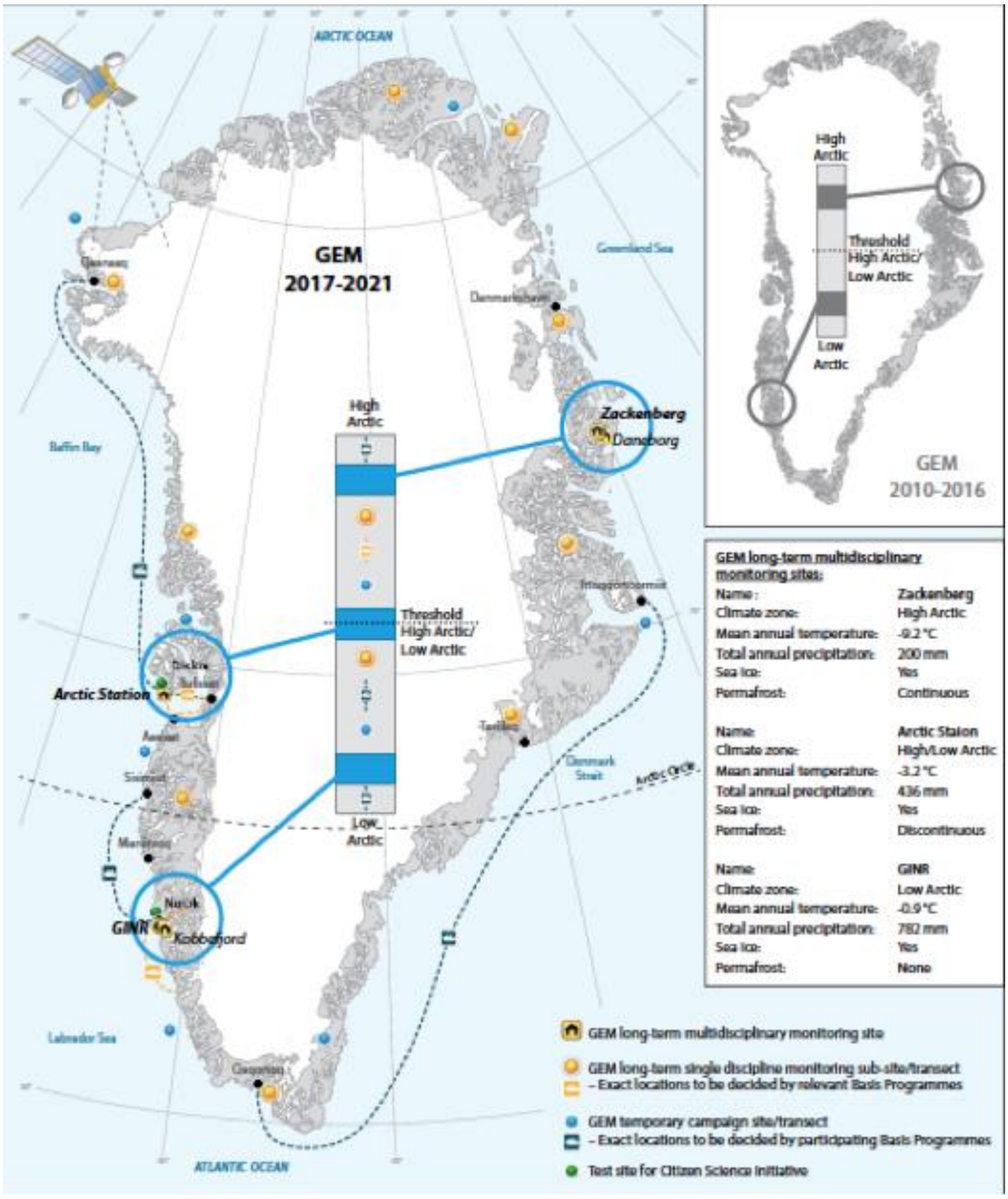


Figure 10. Sampling sites included in the Greenland Ecosystem Monitoring Programme.

2.5 GEUS

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

The *Programme for Monitoring of the Greenland Ice Sheet* (PROMICE) is as 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); it started in 2007.

A central part of PROMICE is the network of presently 22 automatic weather stations (AWS) (Fig. 11) 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. In this deliverable we primarily consider the meteorological observations that are an integrated part of PROMICE.PROMICE is committed to maintain an accessible, safe and thoroughly documented database for storing and disseminating the data free of charge to the climate research community.

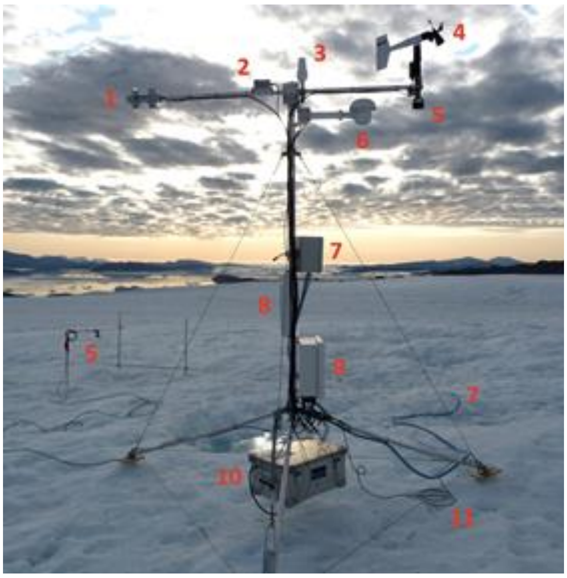


Figure 11. PROMICE automatic weather station UPE_L. 1: radiometer. 2: inclinometer. 3: satellite antenna. 4: anemometer. 5: sonic rangers. 6: thermometer and hygrometer. 7: pressure transducer. 8: solar panel. 9: data logger, barometer and GPS. 10: battery box with 4 × 28 Ah batteries. 11: 8-level thermistor 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. 12). 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 one kilometer from the ice sheet margin). The AWSs 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 ten-minute time intervals, with all data stored locally awaiting collection during maintenance visits. Additionally, 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.

The spatial coverage is largely determined by what is feasible from a logistical/economical point of view, while maintaining an ice-sheet-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 are also expected to be higher 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.

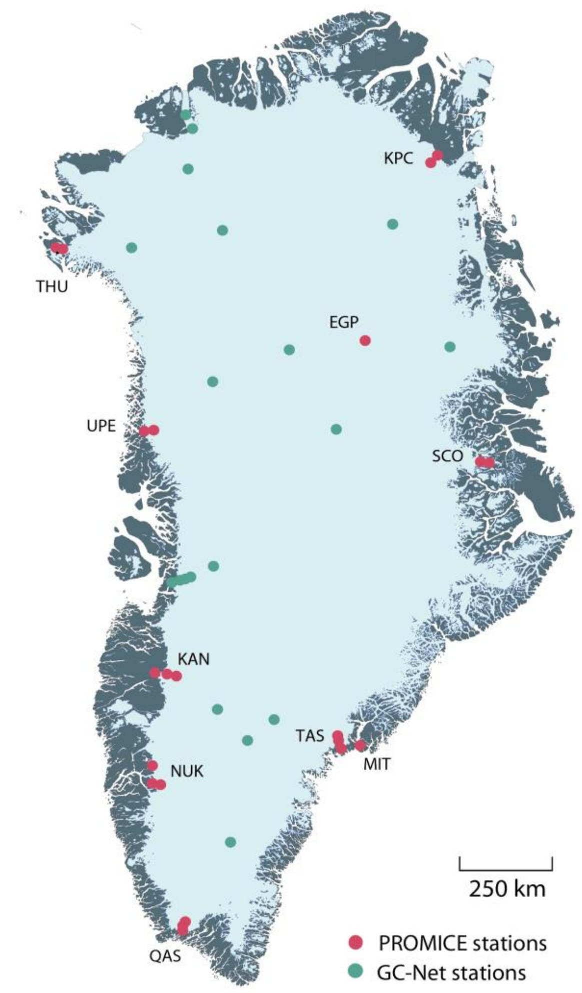


Figure 12. Location of PROMICE and GC-Net automatic weather stations. Note that a number of these stations have been discontinued (primarily GC-Net stations).

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; see Fig. 13. 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. An example of monthly mean data from the station SCO-L is provided in Fig. 14.

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 that frequently experiences extreme and severe weather conditions. 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. 11). The free-floating tripod design, the weather conditions and the power requirements, puts constraints on what is feasible in terms of instrumentation.

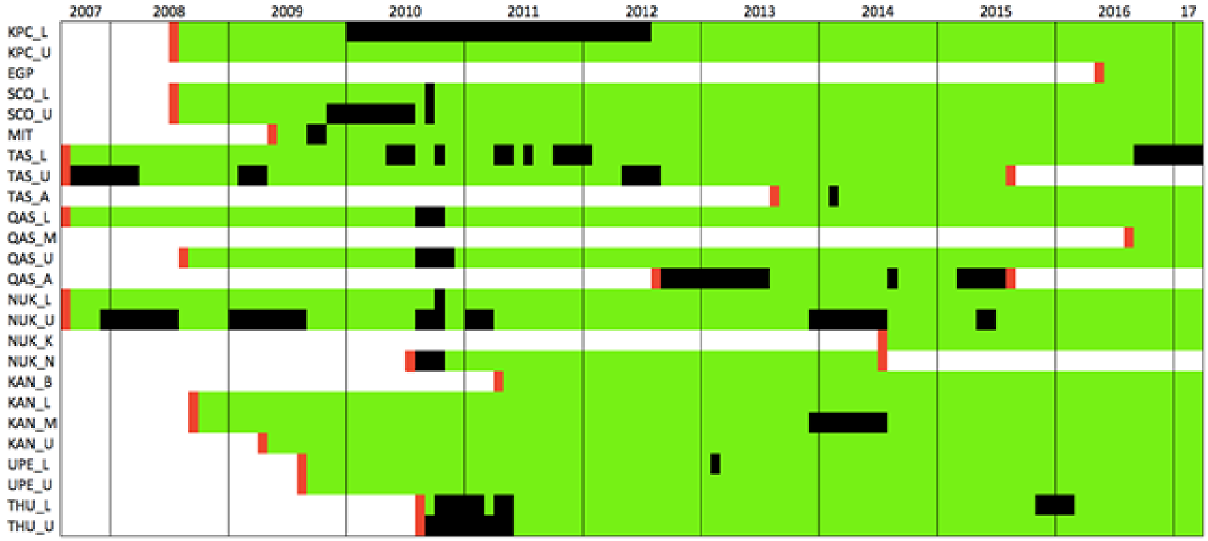


Figure 13. Air temperature measurement coverage (92% total) for all PROMICE weather stations in green. Red markers indicate the installation/removal of the stations. Data gaps are indicated in black.

Our analysis points to 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 amount of snow in 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 happening over the Arctic region. Rain has the 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 select 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 not to jeopardize the core station operation. Over time, these new instruments will be integrated in the standard station setup and established at all the stations where these parameters are relevant.

2.5.2 The Greenland Climate Network

The Greenland Climate Network is an effort originally initiated through the *Program for Arctic Regional Climate Assessment* (PARCA) and has been funded since 1995 by *NASA* and the *National Science Foundation* (NSF). The GC-Net stations were primarily deployed in the period 1995-2000. Currently, some 20 automatic weather stations (AWS) are collecting climate information on Greenland's ice sheet (see Figs. 15 and 16). Three more locations were used earlier, but has been abandoned. Each AWS is equipped with a number of instruments to sample the following:

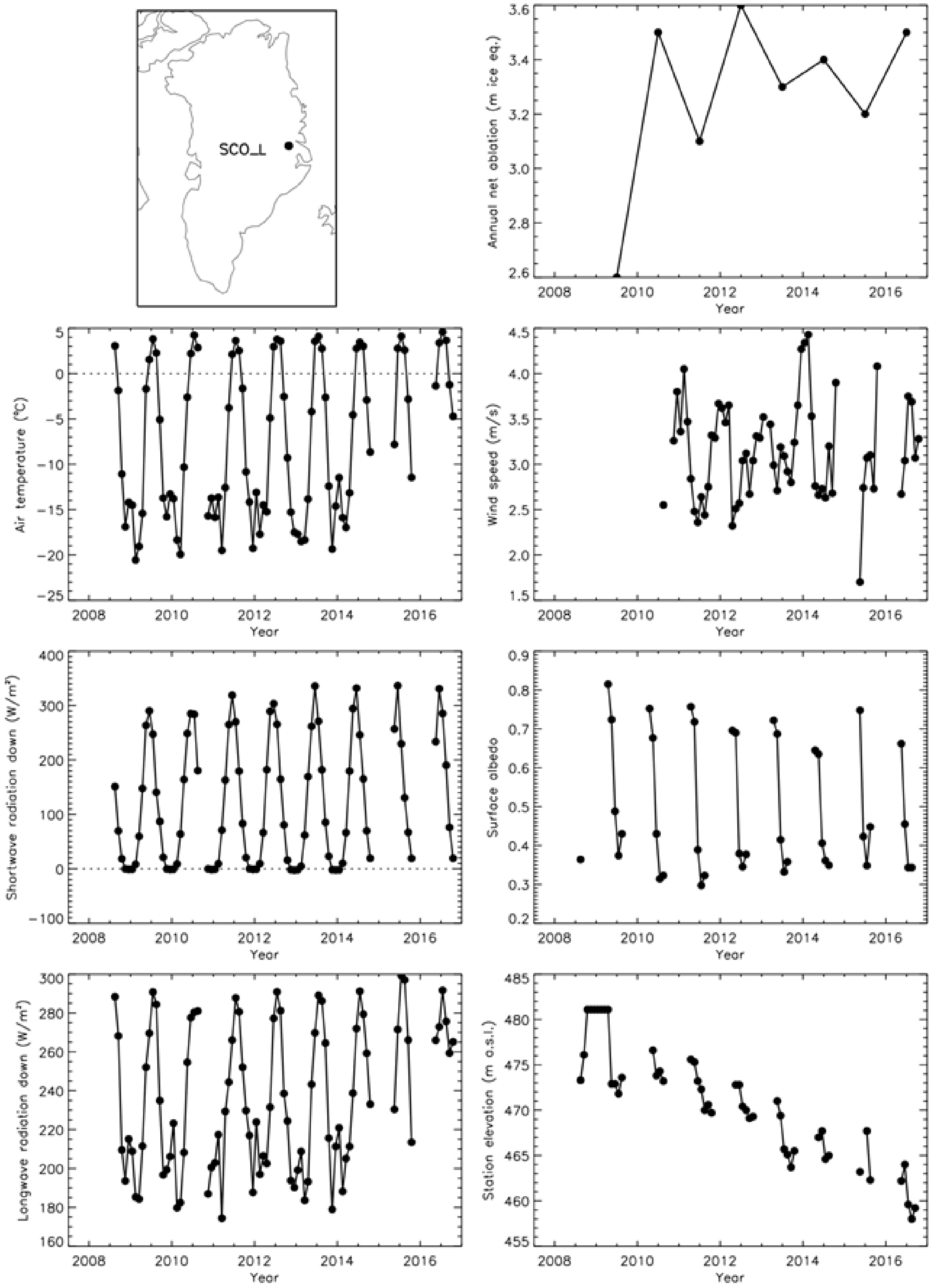


Figure 14. Example of monthly mean data from the PROMICE station SCO-L which is situated on Violin Gletsjer, an outlet glacier from the Greenland Ice Sheet near Scoresbysund fjord in central East Greenland.

- air temperature, wind speed, wind direction, humidity, pressure
- accumulation rate at high temporal resolution to identify and resolve individual storms
- surface radiation balance in visible and infrared wavelengths
- sensible and latent heat flux fluxes
- snowpack conductive heat fluxes

Hourly average data are transmitted via a satellite link (GOES or ARGOS) throughout the year. In addition, measurements are stored in solid-state memory. The system is powered with two 100 Ah batteries, charged by a 10 or 20 W solar panel. The satellite data-link is powered by two separate 100 Ah batteries connected to a 20 W solar panel. This setup guarantees continuous data recordings and storage, even in the case of satellite transmission failure. The design lifetime of the instrumentation is 5 years.

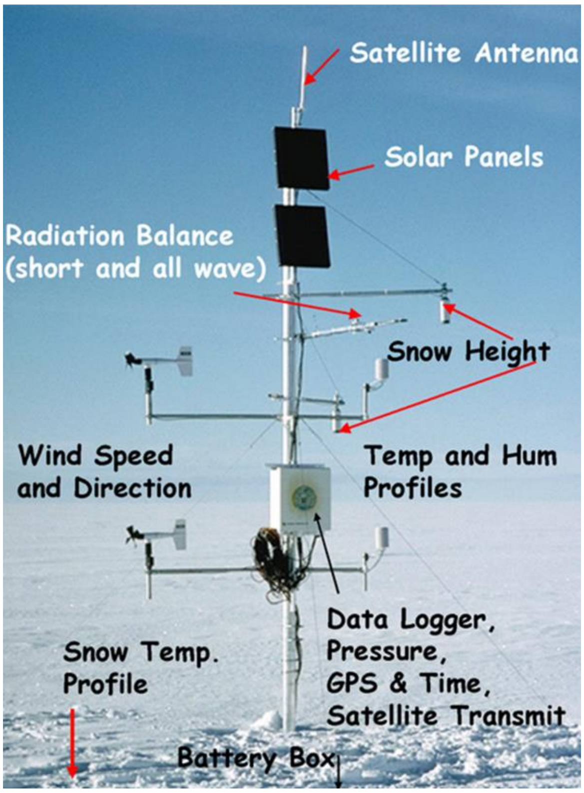


Figure 15. A GC-Net automatic weather station, with instruments mounted on a pole inserted deep into the snow. The battery box and snow temperature profile is below the surface. Each year the pole is extended as more snow accumulates.

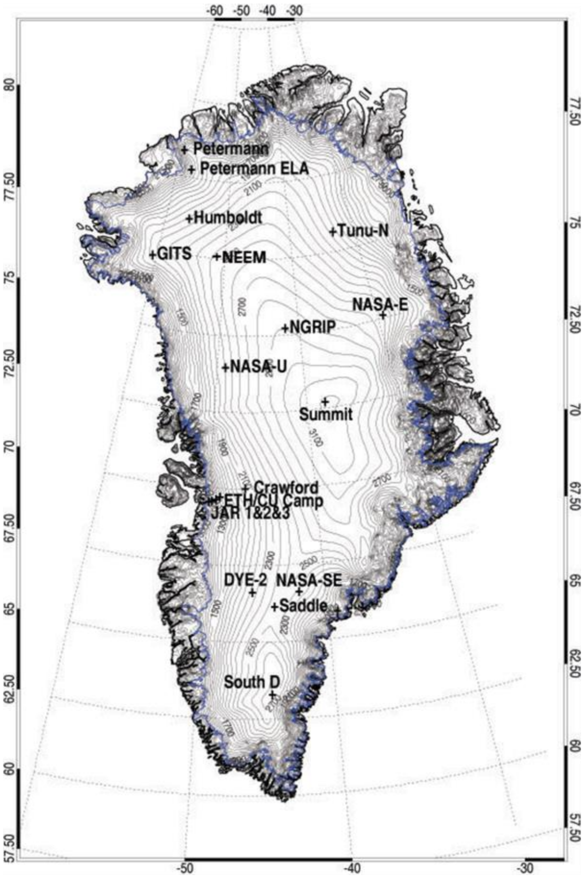


Figure 16. Overview map of the Greenland Climate Network stations.

The GC-Net is mainly operating in the accumulation zone of the Greenland Ice Sheet, except for a few stations north of Ilulissat (JAR-1, -2, -3, Swiss Camp and Petermann, of which not all are currently active). The goal has been and is to quantify the current accumulation rate and the surface climate of the accumulation zone. The automated measurements by the stations are supplemented by snow pit information gathered on the annual visits, providing the snow water equivalent/snow density data.

GC-Net was initiated as a research project and remains an independent effort supported by project funds, rather than an institutional or national monitoring effort. Data is provided on request with basic post-processing and data quality flagging. With a time span of over 20 years (some stations approaching 30 years of operation) the time series available from GC-Net are of primary importance and yet remain vulnerable in terms of funding sustainability, as they are depending on a single Principal Investigator to ensure continued operation.

2.6 FMI

2.6.1 Radiosonde sounding network and Integrated Global Radiosonde Archive

The global radiosonde network was established for operational weather service purposes. Radiosoundings are made by national meteorological institutes and transmitted over *Global Telecommunications System* (GTS). However, radiosoundings are important also for climate monitoring and for research application, from climatology to studies of atmospheric physical processes. The set of sounding stations has varied over time and equipment has also been developed and changed. This assessment based on the situations as of 2017 (Fig. 17).

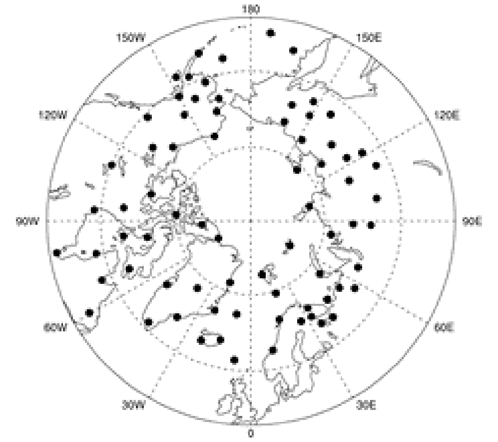


Figure 17. Permanent sounding station in the Arctic in 2017.

The radiosounding data collection included in this assessment is the *Integrated Global Radiosonde Archive* (IGRA), administered by the *National Center for Environmental Information* (NCEI) of the *National Oceanic and Atmospheric Administration* (NOAA). The goals of IGRA are to: 1) combine as many reliable data sources as possible into one radiosonde archive; 2) develop and apply quality assurance algorithms removing gross errors in the data; 3) implement an automatic system for updating the archive on a daily basis; 4) provide unrestricted online access to the data (Durre et al. 2006). IGRA provides a comprehensive set of radiosoundings from historical times to present, updated in near real time.

2.6.2 Long-term surface-based atmospheric composition measurements

Atmospheric composition observations cover a wide range of parameters, including gaseous and particulate components such as greenhouse gases, trace gases and aerosol particles. The majority of long-term composition measurements in the Arctic belong to the *World Meteorological Organization* (WMO) *Global Atmospheric Watch* (GAW) programme. The basis of GAW are the surface-based observations at Global, Regional and Contributing stations belonging to this network (Fig. 18). Data of known quality and with sufficient documentation and metadata information from the network stations are regularly sent to the six GAW World Data Centres.

In the context of atmospheric composition, additional important networks of observations include e.g. the European research infrastructure networks for greenhouse gas observations, *Integrated Carbon Observation System Research Infrastructure* (ICOS), *Aerosol, Clouds, and Trace gases* (ACTRIS) and the pan-Arctic network of Arctic observatories *International Arctic Systems for Observing the Atmosphere* (IASOA). Of these, ICOS and ACTRIS, described in detail below, present well-structured governance and strict rules for data collection and format, providing services for education and improvement of data quality, while IASOA is a collaborative network with no requirements for data presentation or quality. However, as such, focusing merely on the Arctic, IASOA is one of the key bodies in bringing the observations together and providing a link to each data collections.

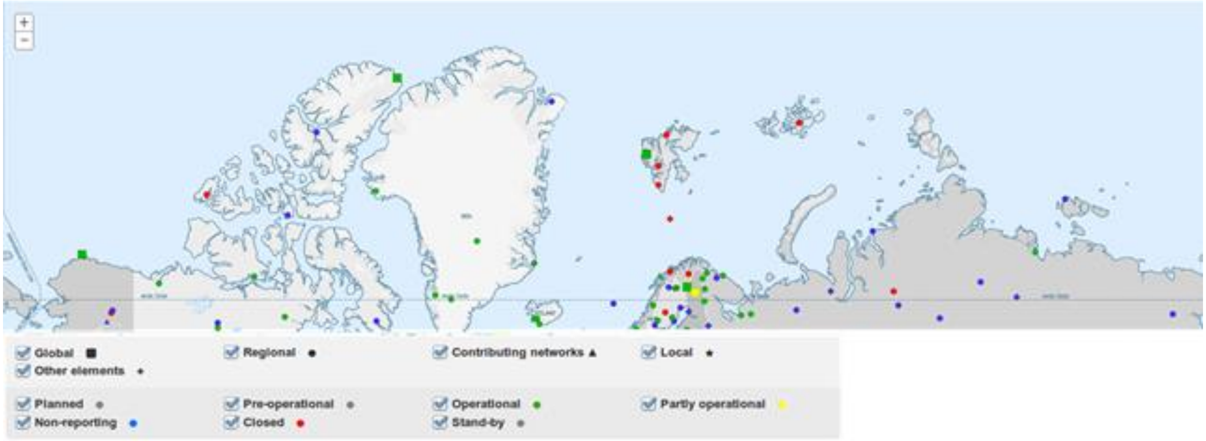


Figure 18. WMO GAW network stations in the Arctic (from: https://gawsis.meteoswiss.ch/GAWSIS on December 8, 2017). Included are all stations: Global, Regional, Contributing, Local and Other Elements, as well as those operational, planned or already closed.

WMO GAW requirements are specified for each measured variable separately. These, in general, are in line with ICOS and ACTRIS requirements for similar observations. However, surveillance of obeisance of these requirements and a further development of measurement techniques is so far the best taken in practice in ICOS and ACTRIS with regular demands for auditing and calibrations. However, as most observations belong to GAW only (although some of them in Europe are also part of various other research infrastructures), our assessment for INTAROS is focused on selected composition variables from Global and Regional GAW stations.

The selected aerosol variables, found most frequently measured in the Arctic, were: aerosol number, size distribution, and scattering and absorption coefficient. It has to be noted that aerosol variables measured in the Arctic are typically highly variable between stations, and this is by far not a comprehensive list. However, it gives an overview of those variables best documented and most often used, as well as giving a good idea of the geographical coverage of Arctic aerosol data. The aerosol number concentration is currently measured at four (4) Global stations: Barrow (USA), Alert (Canada), Ny Ålesund (Norway) and Pallas-Sodankylä (Finland). The earliest time series dates back in the beginning of year 1990. In addition, a few Regional stations (around 4), at the moment measure the aerosol total number concentration. Aerosol absorption coefficient is measured at four (4) Global stations and aerosol scattering at three (3) Global stations. Aerosol size distribution is measured at two (2) Global and two (2) Regional stations in the Arctic. Aerosol data are centrally collected and distributed by the World Data Centre for Aerosols (WDCA), hosted by the *Norwegian Institute for Air Research* (NILU). All the stations reporting aerosol data to WMO GAW database from the Arctic are also part of IASOA network and a few stations in Europe additionally belong to European projects (e.g. ICOS or ACTRIS). Metadata along with the corresponding data files summarize the basic information on measurements which, however, are described in more detailed in scientific publications, along with the typical uncertainties encountered and recommendations given (e.g. Müller et al., 2011a;b, Wiedensohler et al., 2012; 2017).

Columnar ozone measurements are important in the Arctic. They are currently measured at four (4) Global GAW stations (Barrow, Alert, Pallas-Sodankylä, New Ålesund) in the Arctic, either using a Brewer or a Dobson instrument. Most of these time series date back to 50's – 70's, thus providing data to follow the lifecycle of tropospheric ozone loss and slow recovery for several centuries. Columnar ozone measurements are additionally ongoing at least on nine (9) Regional stations in the Arctic, as per information available. In addition to these, some stations (at least eight (8) in total) perform ozone soundings or measure the ozone profile with ground-based instruments. The *World Ozone and UV radiation Data Centre* (WOUDC), hosted by *Environment Canada*, collects and distributes the data on ozone and as well as on UV radiation.

2.6.3 Integrated Carbon Observation System (ICOS)

The European Research Infrastructure ICOS (Integrated Carbon Observation System) is dedicated to the coordinated and standardized long-term measurement of greenhouse gases, especially carbon dioxide, methane, nitrous oxide, and water vapour, and their fluxes. There are three major station types: Ecosystem stations measuring fluxes of CO_2, CH_4, H_2O and heat; Atmosphere stations continuously measuring greenhouse gas concentrations of CO_2, CH_4, CO and radiocarbon-CO_2; and Ocean monitoring the carbon exchange between the surface ocean and the atmosphere, ocean acidification, surface temperature and salinity. The ocean measuring component includes fixed stations, research vessels, and Voluntary Observatory ships. Locations of ICOS stations within the AMAP region are provided in Fig. 19; note that this figure only provides a sample of the ocean tracks.

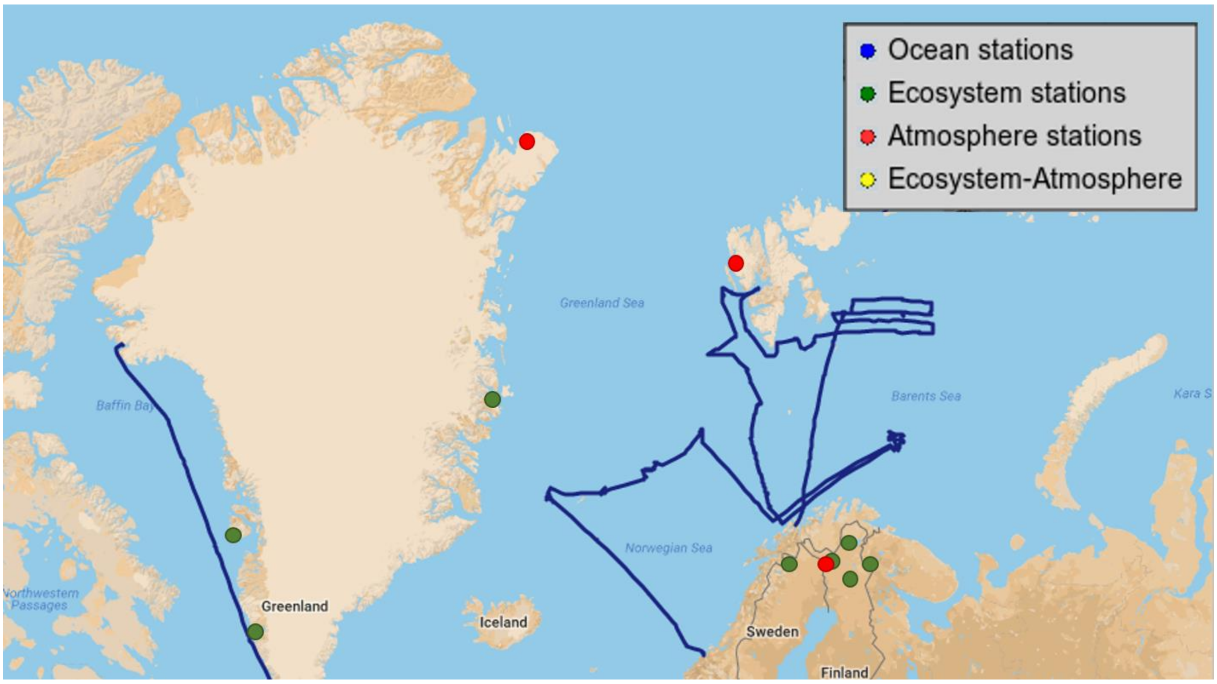


Figure 19. Map of current ICOS stations within the AMAP region. Not all ocean tracks are displayed.

All data are treated and quality controlled with the same algorithms, with data and elaborated products available through the *ICOS Carbon Portal* (https://data.icos-cp.eu/), hosted by the University of Lund (Sweden) and Wageningen University (Netherlands), and is located in Lund, Sweden. Comprehensive metadata is available for all data products.

2.6.4 Aerosol, Clouds and Trace gases infrastructure (ACTRIS)

The European Research Infrastructure ACTRIS (Aerosol, Clouds and Trace Gases Infrastructure network) currently has two long-term stations in the AMAP region (Ny Ålesund & Pallas-Sodankylä) providing cloud profile information at a very high temporal and vertical resolution. Cloud profiling combining cloud Doppler radar, lidar, and multichannel microwave radiometer enables categorization of cloud targets and estimation of cloud properties including: cloud fraction, cloud phase, cloud ice water liquid water content, in-cloud turbulence, all at resolutions better than 50 m in the vertical and 30 s in time (Illingworth et al., 2007). Data is available through the ACTRIS portal (http://actris.nilu.no).

ACTRIS provides a comprehensive suite of evaluation metrics for NWP models. In Fig. 20, winter time boundary-layer cloud fraction shows a weak diurnal cycle, as might be expected, and is much higher than in summer. The model compares favorably with observations, but lacks an appreciable proportion of mid-level cloud. The model displays similar statistics for mean cloud fraction (Fig. 21), but because the amount-when-present is too low over much of the vertical profile, the mean cloud fraction profile is underestimated. The mean skill score profile suggests boundary-layer clouds are the most difficult to forecast. Note that the 'traditional' ETS metric also shown here is not reliable when dealing with rare events, hence, also shows low skill for cloud above 9 km; such clouds are uncommon at Sodankylä.

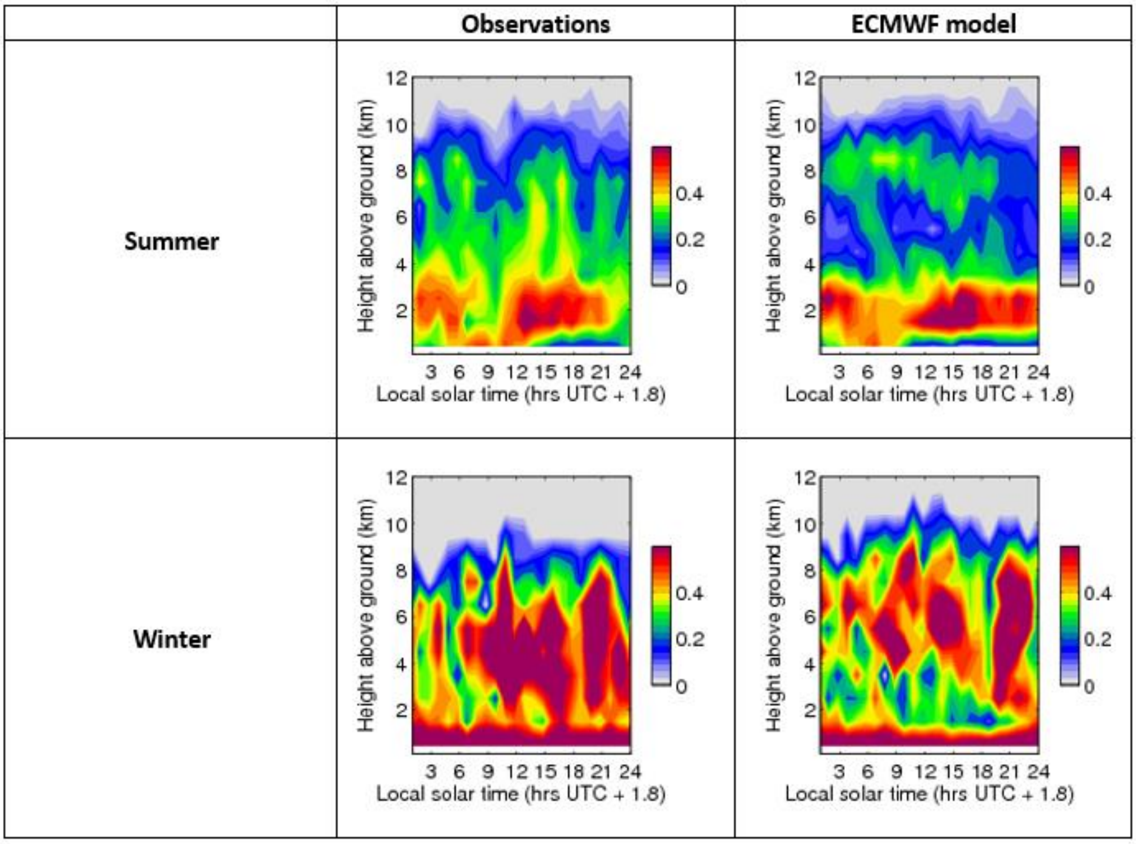


Figure 20. ACTRIS-Cloudnet evaluation of ECMWF cloud fraction at Sodankylä – diurnal composites of cloud fraction (colour scale indicates cloud fraction).

Atmospheric Radiation Measurement program (ARM, https://www.arm.gov/) of the US Department of Energy also operate cloud profiling sites using similar instrumentation; two located in the AMAP region (Barrow and Oliktok, Alaska). All data obtained through the ARM Facilities is monitored for quality and available free of charge through the *ARM Data Center* (https://www.archive.arm.gov/discovery/). ARM provides similar cloud products and metadata as ACTRIS, and offers a DOI service for all data products. There have also been long-term campaigns at Summit (Greenland) and Eureka (Nunavut, Canada) with instruments of similar capability (see Shupe et al., 2011), together with a number of shipborne campaigns. The high resolution cloud profiling data provided by similar sites has been used to continuously evaluate the representation of clouds in climate and weather forecast models (Illingworth et al., 2007; Morcrette et al., 2012; Sotiropoulou et al., 2016).

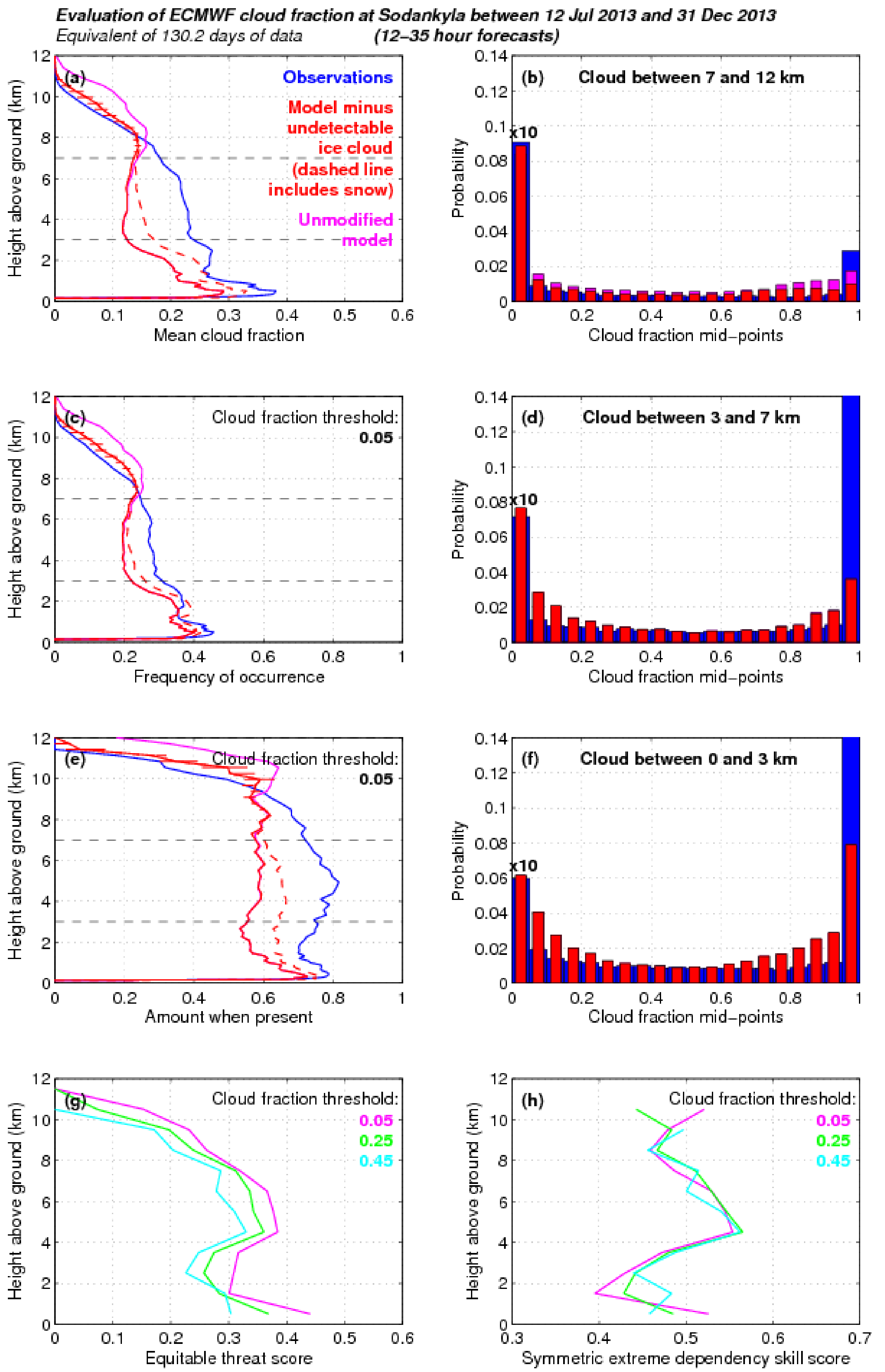


Figure 21. ACTRIS-Cloudnet evaluation of ECMWF cloud fraction at Sodankylä – climatological metrics.

Such evaluations have often shown that models are able to capture the vertical profile of cloud fraction reasonably well, especially the frequency of occurrence, although low clouds are notoriously difficult and other cloud features, such as cloud phase, are very difficult to predict accurately.

2.6.5 Meteorological observations at Sodankylä

Figure 22. Snow depth station in forest opening.

At the FMI Sodankylä station, precipitation and air temperature, among various other meteorological parameters, are measured by an automatic weather station. Daily updated 10-min average values since 2006 are available from http://litdb.fmi.fi/luo0015_data.php as csv text files. These data are the official meteorological measurements from Sodankylä station and go through both an automated and a manual quality control. Measurements are compared to warning and error limits set based on parameter, time of year, station location and climate. If a measurement is outside a warning limit, it is flagged as suspicious; similarly, outside an error limit, it is flagged as erroneous.

There are also three weather stations with snow depth and air temperature measurements. One is located on open bog, one in the forest and one in a forest opening (Fig. 22). The stations were established in 2006 (forest stations) and 2010 (bog site). The 10-min average data are available from http://litdb.fmi.fi/ioa0003_data.php and http://litdb.fmi.fi/suo0003_data.php as csv text files separately for each station. These data are not updated in real time, as the data first go through a semi-automatic quality control. Clearly faulty measurements are removed.

2.7 SMHI

2.7.1 Satellite observations of cloud parameters

SMHI has investigated three satellite based long-term cloud property datasets over the Arctic covering 33-year time period from 1982-2014. The datasets are: CLARA-A2 (Karlsson et al., 2017), PATMOS-x (Heidinger et al., 2013) and ESA Cloud_cci (Stengel et al., 2017). They provide the longest record available of cloud properties globally, including over the Arctic and are based on AVHRR sensors flown onboard a series of NOAA satellites. All three datasets are based on exactly same calibrated radiances, but differ in their retrievals algorithms. For example, cloud masking in PATMOS-x is based on Naïve Bayesian philosophy, while CLARA-A2 employs hierarchical decision tree tests anchored in physical features, while the Cloud_cci product uses neural network approach. This intercomparison helps to understand the range of observational uncertainties owing purely to algorithm differences. Both Level 3 (monthly mean) and Level 2b (gridded daily) products from each dataset are analysed. Various cloud properties are intercompared, including cloud fraction, cloud top temperature and height, cloud liquid and ice water paths. Low, medium and high clouds are also separately intercompared. Apart from these traditional comparisons, the process oriented evaluation of these datasets is also carried out, involving investigating cloud response to different modes of natural variability and moisture intrusions into the Arctic.

Due to brevity of space, only few results are discussed here. Fig. 23 shows the intercomparison of total cloudiness from the three datasets for the summer half year in the Arctic. Over the Arctic Ocean, the differences in cloud fraction are less than 10% among the datasets during the JJA months. However, during peak melting in September and later in October, the disagreements between the datasets increase up to 25%. PATMOS-x shows higher cloud fraction values during the beginning of autumn compared to CLARA-A2. In winter the differences are too large to meaningfully evaluate.

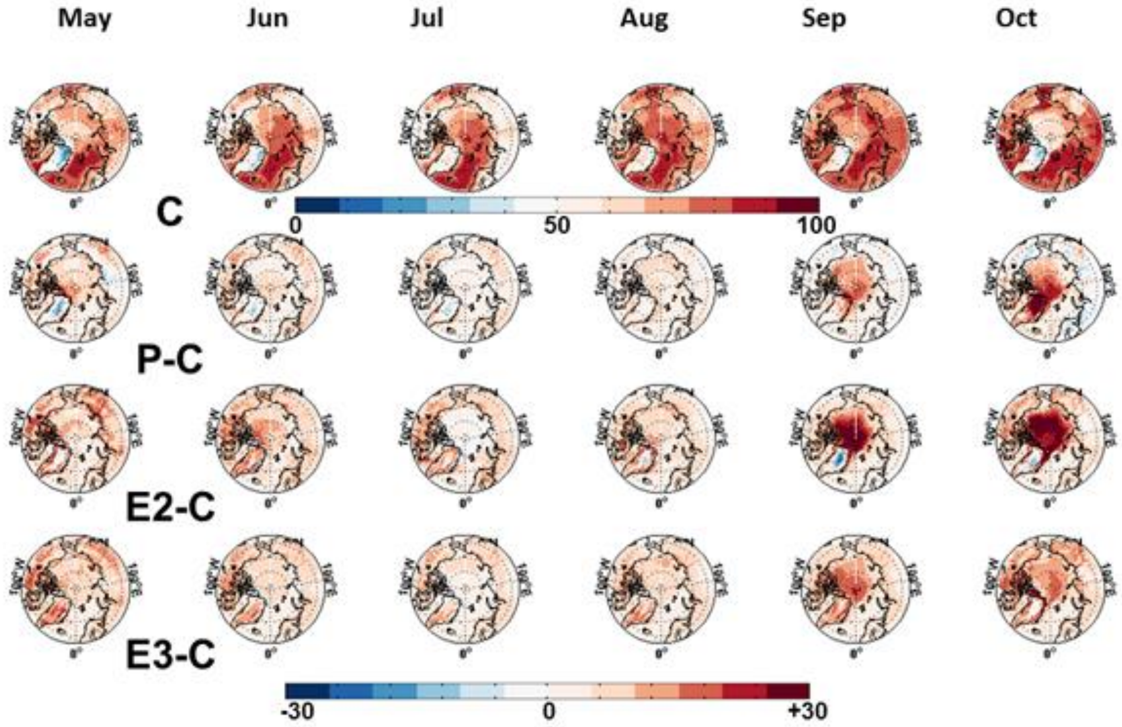


Figure 23. Intercomparison of total cloud fraction derived from CLARA-A2 (C), PATMOS-X (P) and version 2 and 3 of ESA Cloud_cci (E2 and E3 resp) datasets. The first row shows absolute values of total cloudiness based on CLARA-A2 and the other rows show differences with respect to CLARA-A2. The differences are based on 33-year period (1982-2014).

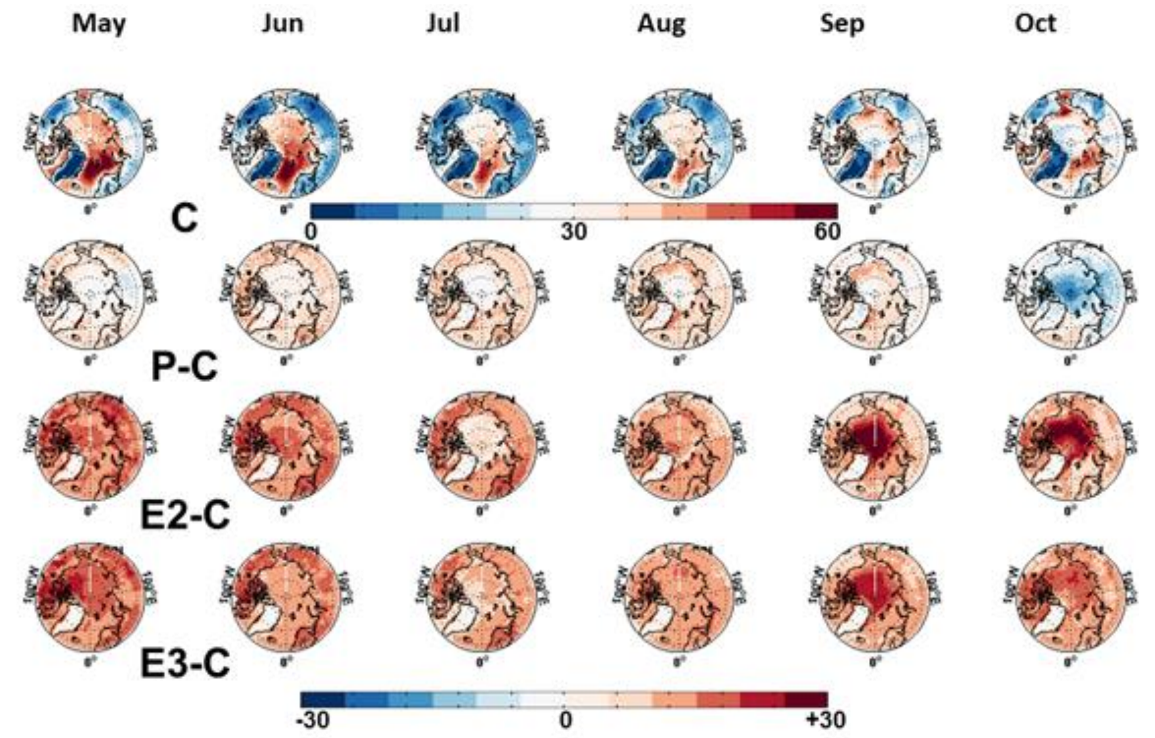


Figure 24. Same as in Fig. 2.7.1, but for the low level clouds.

Since low level clouds are quite important in the Arctic due to their influence on the surface and boundary layer processes, Fig. 24 further shows intercomparison of low level cloud fractions. Here, the strong differences among the datasets start to emerge. During late summer and early autumn, differences of up to 15% along the coastal zones with respect to PATMOS-x and to up to 30% in the multiyear sea-ice parts of the Arctic Ocean with respect to Cloud_cci datasets are observed. In October, PATMOS-x shows lower amounts of low-level clouds compared to CLARA-A2. During early summer, however, the differences between PATMOS-x and CLARA-A2 remain below 5%.

Fig. 25 shows the differences in cloud top temperatures (CTT) retrieved in these datasets. Compared to CLARA-A2, PATMOS-x and Cloud_cci show opposite differences in CTTs. During summer months, the CTTs in PATMOS-x are 3-5K lower and during early autumn, they are up to 15K colder. This is mainly due to the fact that, compared to CLARA-A2, PATMOS-x has higher high level cloud fraction and thus much colder cloud top temperatures. Cloud_cci, on the other hand, shows slightly higher cloud-top temperatures compared to CLARA-A2, with differences reaching up to 3K over the ocean areas and up to 5K over land areas.

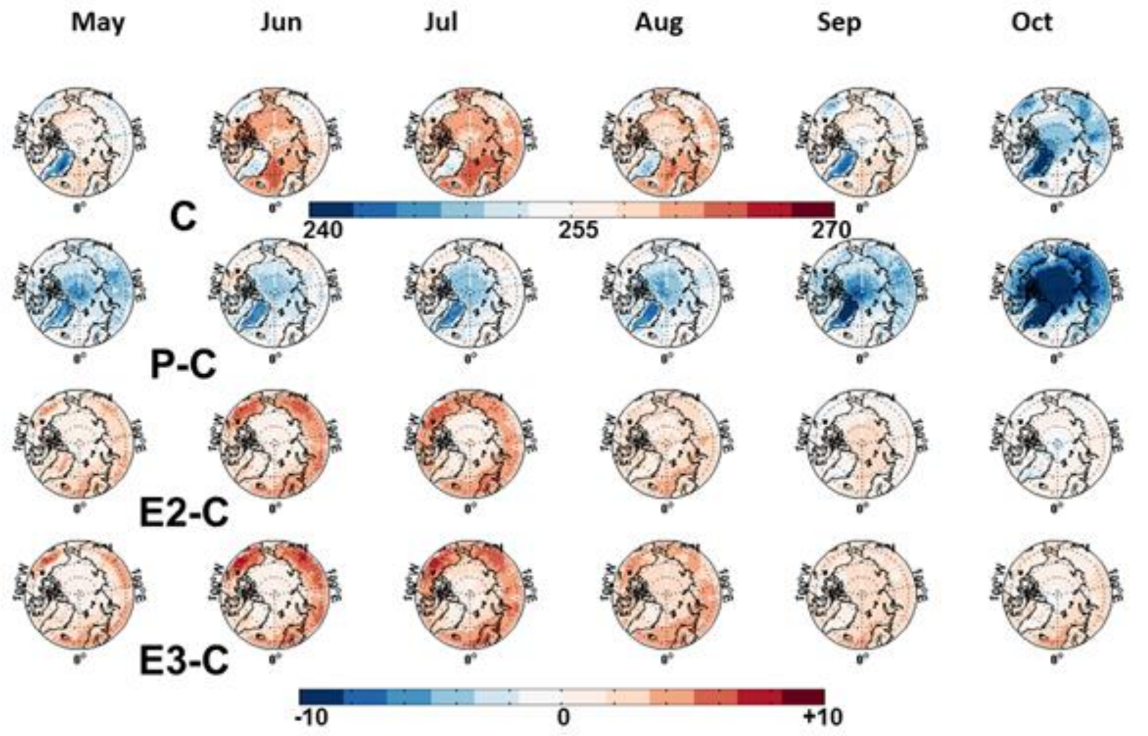


Figure 25. Same as in Fig. 23, but for cloud top temperatures (in K).

Finally, Fig. 26 shows climatological cloud liquid water paths for the summer months derived from these datasets. The differences over both the Arctic Ocean and surrounding land areas are very high among the datasets. These differences expose the limitations of these datasets with regard to cloud phase discrimination and corresponding retrievals philosophies, rendering them of limited use for climate studies.

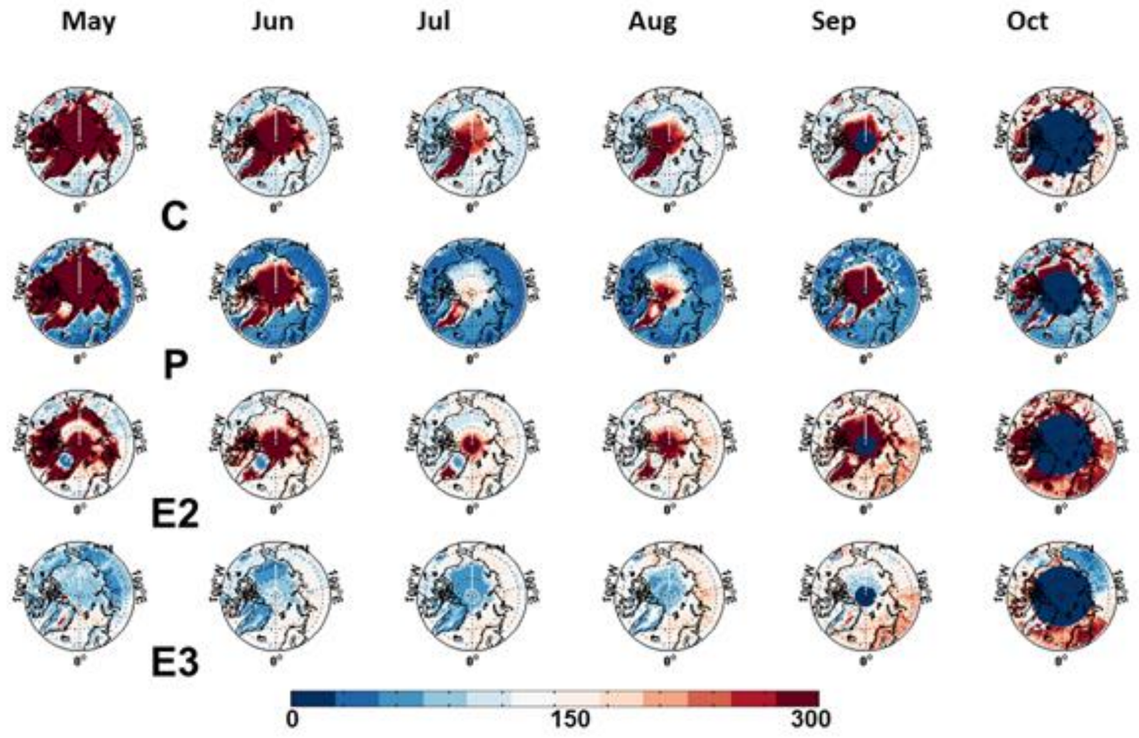
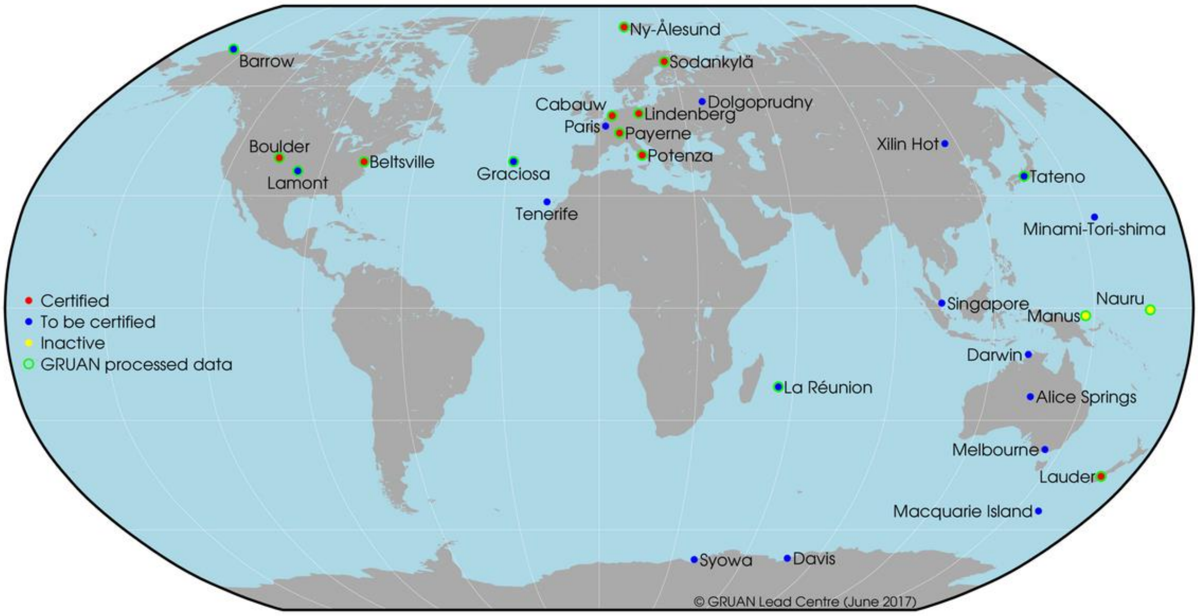


Figure 26. Climatological mean cloud liquid water paths (g/m2) during summer half year.

2.8 NUIM

2.8.1 GCOS Reference Upper Air Network (GRUAN)

The GCOS Reference Upper Air Network (www.gruan.org) consists of a global collection of stations undertaking high quality, metrologically traceable measurements of the atmospheric column. Presently, data streams are limited to the Vaisala RS-92 radiosonde product. Work is ongoing on the Vaisala RS-41, a range of other manufacturers sondes as well as frostpoint hygrometers and a range of remote sensing equipment.



© GRUAN Lead Centre (June 2017)

Figure 27. GRUAN network map, available at www.gruan.org

The RS-92 product is described in Dirksen et al. (2014) and also in three product traceability and uncertainty documents arising out of the H2020 GAIA-CLIM project (http://www.gaia-clim.eu/page/product-traceability-and-uncertainty-documents). Data are available via NOAA NCEI's ftp server, as cf-compliant netcdf files. All data files include both a best estimate and a metrologically traceable uncertainty estimate on the profile. Only those data that have passed quality checks are provided to users. The GRUAN data product is consistent with, but distinct from, the manufacturer processed data available from e.g. IGRA. No further processing is necessary for evaluation in INTAROS.

GRUAN sites within the Arctic domain are: Ny Alesund, Barrow and Sodankyla (Fig. 27). Data are available for these stations starting in 2009 (Barrow), 2006 (Ny Alesund) and 2007 (Sodankyla). With the transition to RS41 the data streams either diminish in frequency or stop in 2016/17. Work is ongoing to prepare an RS41 product which shall follow similar traceability principles to that of the RS92 product.

2.8.2 GOS surface metrological observations

NUIM is the lead on the Copernicus Climate Change Service contract C3S 311a Lot 2 which is concerned with the facilitation of access to global land and marine observations of surface meteorological holdings. Work is in collaboration with NOAA's National Centers for Environmental Information. The work includes the collation of available global, regional and national level holdings of land surface-based meteorological holdings from standard meteorological stations, their harmonization, and their provision via the C3S data store. Work is ongoing in parallel to INTAROS and submissions of data facilitated by INTAROS are welcomed.

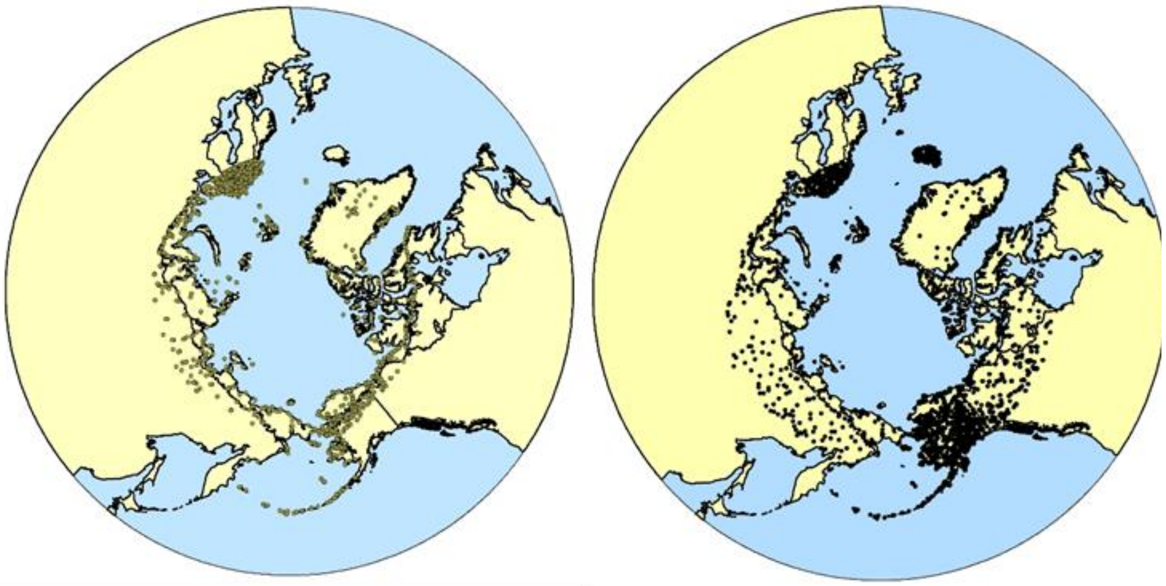


Figure 28. Daily (left) and sub-daily (right) station records available within the INTAROS defined Arctic domain. Each dot represents a station. No attempt is made at this stage to denote station start and cessation dates. At any point in time only a subset of these stations have been in operation.

The available data contain a paucity of metadata beyond positional metadata. However, existing intercomparisons and regulatory materials allow at least indicative knowledge of observing practices and impacts on representativity and uncertainty. Data are available at a mix of observation-resolution, daily aggregates and monthly aggregates. Within the Arctic domain there are several thousand potential stations arising from several tens of underlying sources. These sources likely contain gross duplication such that the final count shall be smaller than the current apparent station counts. There shall be several releases of harmonized holdings over the course of the INTAROS project. Fig. 28 shows daily and sub-daily files available within the Arctic domain as defined for INTAROS; stations outside this domain are excluded.

2.9 MPG

2.9.1 Greenhouse gas flux measurements from tall towers

Within INTAROS 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. For this deliverable, only the tall tower (Fig. 29) component will be reported.

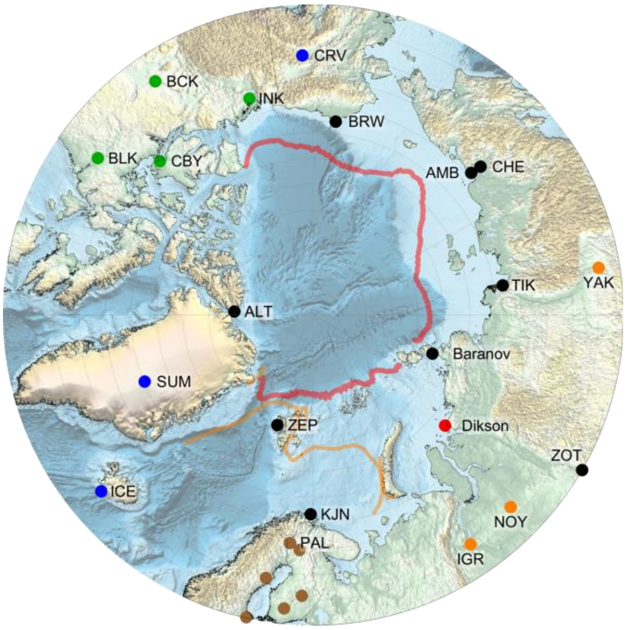


Figure 29. Overview on the currently active network of atmospheric tall towers monitoring greenhouse gas mixing ratios in the Arctic domain. ICOS network (brown); Environment Canada (green); JR-network (orange); continuous observations from various operators (black); flask observations from various operators (blue), and site under development (red).

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 setup 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 research 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 which 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 the figure below. The atmospheric transport simulations that are required to link each of these towers to its source region, and the temporal variability therein, are currently 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.

2.10 NIVA

2.10.1 Barents Sea FerryBox

The Barents Sea FerryBox system (King, NIVA) is a suite of sensors deployed on a ship of opportunity, the M/S Norbjørn, that makes ~30 roundtrip voyages annually between Tromsø, Norway (69.675 N, 18.9849 E) and Longyearbyen, Svalbard (78.1227 N, 13.9138 E). Some voyages also stops at Bear Island, Svalbard (74.4522 N, 19.1152 E) and Ny Ålesund, Svalbard (78.9235 N, 11.9099 E). The ship is outfitted with sensors mounted on the deck that measure wind and light-related variables, in addition to a seawater sensor system. Sensors undergo different levels of calibration and validation which are discussed in more detail below.

Data collected by the deck sensors of the FerryBox system are reported as raw data and Level 1: calibrated data in netCDF and are CF-compliant. Data are available typically within one week after acquisition (except for a few cases described in more detail below) and are provided and stored by NIVA. All data collected are treated with the same metadata standards – data collections and data files are accompanied by metadata that can be used independent of external assistance that include geographical coordinates, units, valid range, missing values, etc.). Quality flags are provided for all data that are subjected to the Copernicus Marine Environment Monitoring Service (CMEMS) criteria. When a pass/no pass quality flag is not available, a "no flag provided" flag is assigned. All measurement techniques employed by the FerryBox sensors have been described in peer-reviewed literature and examples of usage are also published (by either our group or other ocean observing groups).

Wind speed and direction are measured using a Gill Wind Observer II. The sensor has been flight proven through use by the meteorological community. Wind speed and direction are corrected for ship movement. The sensor is periodically checked for performance, but no traceable reference materials are used.

Hyperspectral radiance and irradiance is measured using a TriOS RAMSES radiometer. The sensor has been flight proven through the use by the remote sensing community. Raw data are used to calculate Remote Sensing Reflectance (Rrs) values from 400-900 nm. The sensor is periodically calibrated in the lab using a NIST standard, in addition to European-wide group calibration exercises.

2.11 U Helsinki

2.11.1 Pan-Eurasian Experiment (PEEX)

The Pan-Eurasian Experiment (PEEX) initiative (https://www.atm.helsinki.fi/peex), initiated in 2012, is an international, multidisciplinary, multiscale program focused on solving interlinked global problems influencing societies in the Northern Eurasian region and in China. As a part of the program, PEEX is aimed 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) the existing stations 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 the filling the observational gap, especially over the Siberian region, and the development of the 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 exiting stations in Russia. After having detailed information, the station metadata, it would be also possible to make the station specific upgrading plans and having added 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". A station metadata, the detailed descriptions of measured variables and the observation site, enables categorize the stations in a systematic manner and to connect them to international observation networks, such as WMO-Global Atmospheric Watch Program, China Ecosystem Network (CERN), and carry out standardization of data formats. The Russian station metadata collection has been carried out in 2016-2017 and continues in 2018. So far our database covers metadata over 53 stations.

As an INTAROS contribution, the metadata has been received from 11 measurements stations located within the Russian Arctic territories (see Fig. 30). At these stations, long-term continuous measurements for meteorological parameters such the air temperature, relative humidity, wind speed and direction, precipitation are performed.

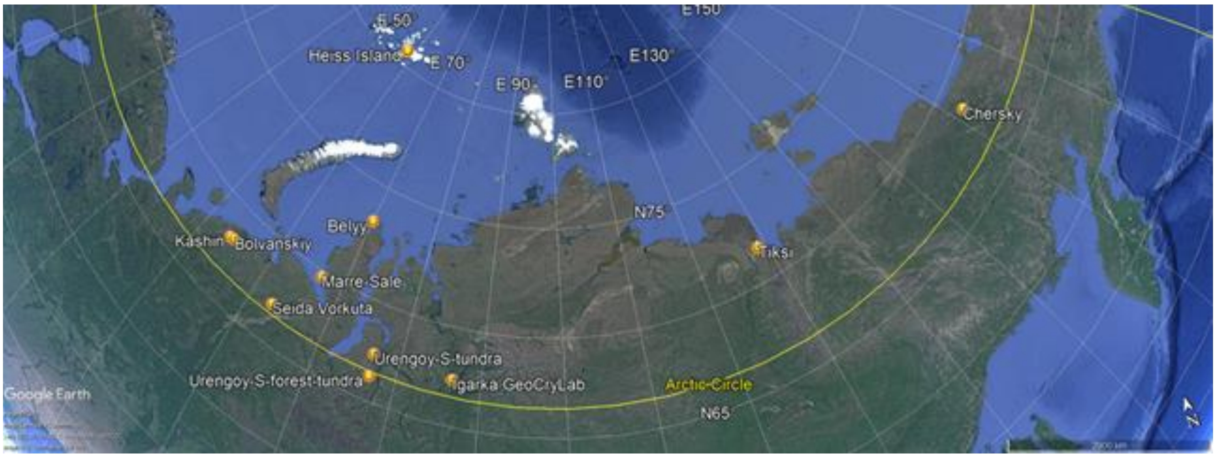


Figure 30. Geographical positions of the selected 11 PEEX Russian Arctic stations (as contribution to the INTAROS project).

The programme of measurements is realized 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) who are the owners of the stations. Measurements at the sites represent more local conditions of the immediate surrounding environment. Data (datasets/ data collections/ time-series of measurements) are available from the owners on request, though direct contacts with the responsible persons (see 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 the current situation, limited information on uncertainty arising from systematic and random effects in the measurements is available. More detailed information on PEEX the stations' metadata is available on request (https://peexdata.atm.helsinki.fi). Comprehensive and quality-controlled measurements (with automated & semi-automated loggers for measurements and for accumulating the data) are performed 4 times per day (at 6 h interval) for air temperature, relative humidity and accumulated precipitation at 2m, as well as for the wind speed and direction at 10 m above the ground.

PEEX will demonstrate separate data analysis for Russian stations as a "show case" basis based bilateral agreement between PEEX Program and the station in question. Based on the metadata inventory PEEX will publish s 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 partner in Russian stations - PEEX collaboration network and to give positive visibility to the station activities.

2.12 GFZ

2.12.1 Airborne trace gas profiles - campaign setup, instrumentation and examples

We contribute data obtained during vertical profile flights from three study areas in the Arctic: The North Slope of Alaska (NSA), the Mackenzie Delta in Canada and the Lena Delta in Siberia (Fig. 31). Three campaigns took place during the growing seasons in both the Mackenzie Delta and the NSA and four campaigns in the Lena Delta including flights during spring (Fig. 31, Table 2). In all three study areas, the flight campaigns consisted of horizontal flight tracks at about 40 m – 80 m above ground level for greenhouse gas flux measurements (see INTAROS reports D2.7 and D2.8) and vertical profile flights within and beyond the atmospheric boundary layer at the beginning and the end of each flight track.

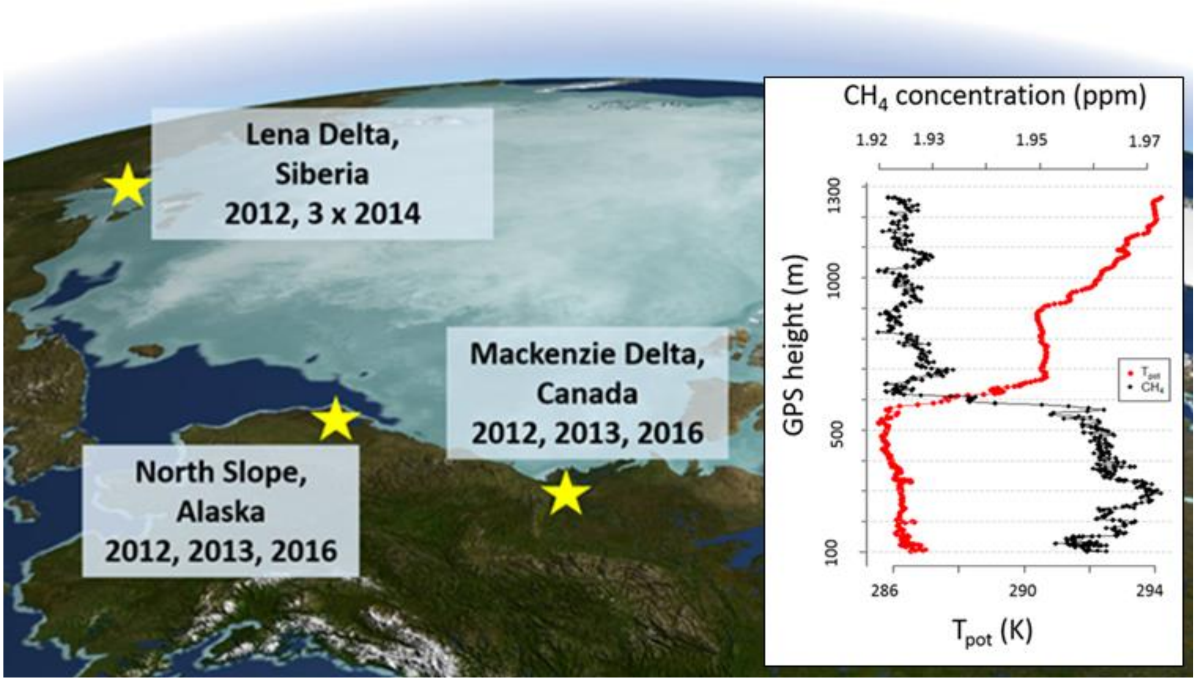


Figure 31. Location of study areas and years of the campaigns. Insert shows an example of methane and potential temperature profiles.

We used two different airborne platforms for the campaigns: The Polar 5 research aircraft (Fig. 32a) of the *Alfred Wegener Institute Helmholtz Centre for Marine and Polar Research* (AWI) for Alaska and Canada and the helicopter-towed Helipod (Fig. 32b) of *Technische Universität Braunschweig* for Siberia. Both platforms, the instrumentation and specifics of the campaigns are described below.

The data sets of the vertical profiles include CH_4 and CO_2 concentration, water vapour, air temperature, air pressure, altitude above ground (radar height), altitude above sea level (GPS height), and the coordinates. The data can be used e.g. to derive the atmospheric boundary layer height across the study areas or to gain information on atmospheric composition. An example is shown as an insert in Fig. 31.

Table 2. Summary of the three campaigns, indicating location, years and dates.

Study area	2012	2013	2014	2016
North Slope of Alaska	28.06.2012–02.07.2012	04.07.2013 – 14.07.2013		25.08.2016 – 03.09.2016
Mackenzie Delta	04.07.2012-10.07.2012	19.07.2013 – 26.07.2013		07.09.2016 – 20.09.2016
Lena Delta	09.08.2012-15.08.2012		06.04.2014 – 22.08.2014	

2.12.2 AIRMETH vertical profiles Polar 5

The research aircraft Polar 5 (Fig. 32a) of AWI was used during AIRMETH (Airborne Measurements of Methane Fluxes) flight campaigns in the Mackenzie Delta, Canada, and on the NSA (Kohnert et al., 2014; Kohnert et al., 2017; Hartmann et al., 2018). On the NSA, data were collected during three study periods: 28 June to 02 July 2012 (41 profiles), 04 July to 14 July 2013 (58 profiles), and 25 August to 03 September 2016 (19 profiles). In the Mackenzie Delta, the study periods were 04 July to 10 July 2012 (42 profiles), 19 July to 26 July, 2013 (47 profiles), and 07 September to 20 September 2016 (56 profiles).

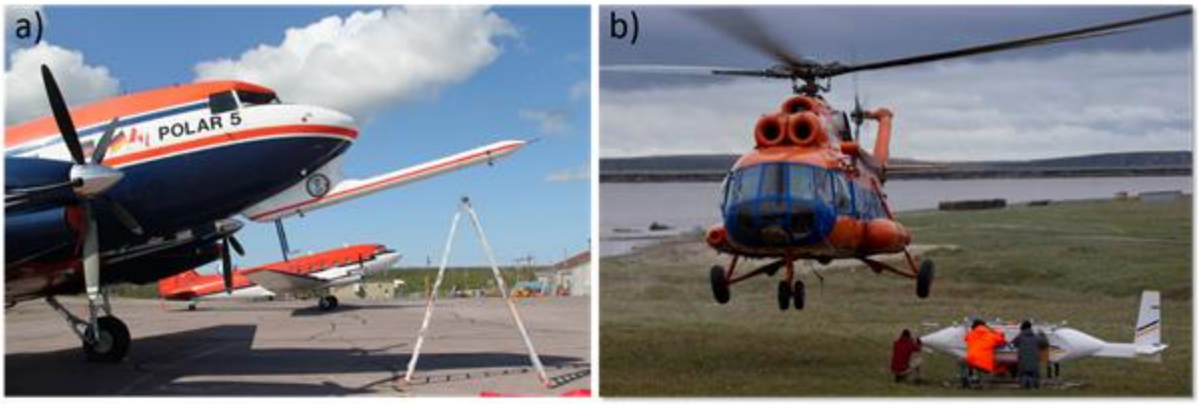


Figure 32. Airborne platforms used for data collection: (a) The Polar 5 research aircraft of the Alfred Wegener Institute, used for the campaigns in Alaska and Canada, and (b) the helicopter-towed sonde Helipod of Technische Universität Braunschweig, used in Siberia.

Each science flight consisted of horizontal flight tracks at about 40 – 80 m above ground level for flux measurements (see D2.7 and D2.8) and vertical profile flights at the beginning and end of each low-level leg (Fig. 33). The profile flights usually extend through the atmospheric boundary layer (ABL) and above. During the profile flights, greenhouse gas concentrations (CH_4, CO_2, water vapour), air pressure and air temperature were recorded to determine the atmospheric composition and atmospheric parameters.

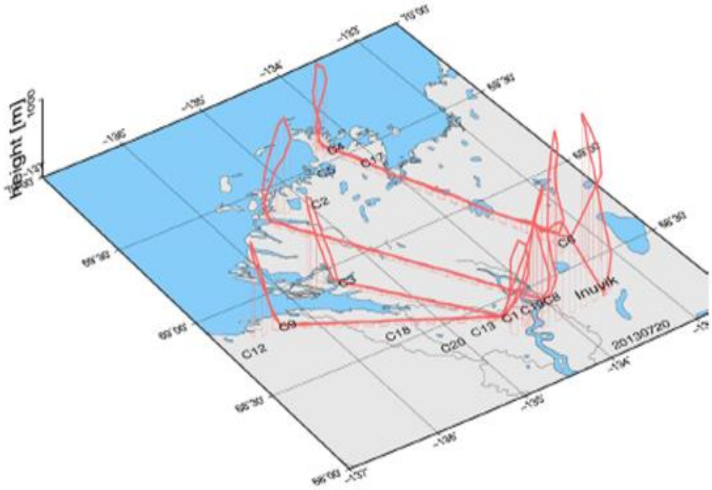


Figure 33. Exemplary flight pattern across the Mackenzie Delta including horizontal flight tracks close to the surface and vertical profile flights. Figure by Jörg Hartmann.

For the gas measurements, sample air was drawn from an inlet tube placed 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). The air temperature was measured with an open wire Pt100 in an unheated Rosemount housing, and air humidity with an HMT-330 (Vaisala, Helsinki, Finland) also placed in a Rosemount housing. The location and altitude of the aircraft were determined 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).

2.12.3 AIRMETH vertical profiles Helopod

The helicopter-towed Helipod (Fig. 32b) of Technische Universität Braunschweig was used in 2012 and 2014 for flight campaigns in the Lena River Delta, Siberia. The flights took place in three periods (Table 2): in April while the delta was frozen and snow covered, in May/June during the ice breakup of the Lena River and in July/August during peak growing season. During these campaigns, that were designed to derive regional flux estimates of methane (CH_4), carbon dioxide (CO_2), sensible and latent heat across the Lena River Delta, also vertical profile flights were conducted at the beginning and end of each flight track.

To measure greenhouse gas concentrations, the Helipod was equipped with two open path Licor sensors; one for CH_4 (Li 7700) and an one for CO_2 and H_2O sensor Li (7500). The wind was measured with a 5-hole probe in combination with a navigation system, air temperature with a Pt100 by Rosemount and a fine wire by Dantec, air humidity by Lyman Alpha sensor L6 (Buck Research), and the location and position by the Gnatti System (Geo++ GmbH).

2.13 IGPAN

2.13.1 Polish station Hornsund

The Polish Polar Station Hornsund (77∘00′N 15 ∘33′E) is located on the northern shore of Hornsundfjord on Wedel Jarlsberg Land in SW Spitsbergen. Warm and humid air transported by extratropical cyclones from lower latitudes and warm West Spitsbergen current have significant influence on the climate, which is mild and maritime, considering its high latitude. The Hornsund meteorological station (WMO 01003; Fig. 34) conducts year-round observations and measurements since its reestablishment in July 1978. It is located on a marine terrace at 10 m a.s.l., 300 m from the shore. Meteorological time series from Hornsund station can be obtained from the database of the Institute of Geophysics Polish Academy of Sciences. Meteorological data in the form of SYNOP are sent every hour to WMO database.

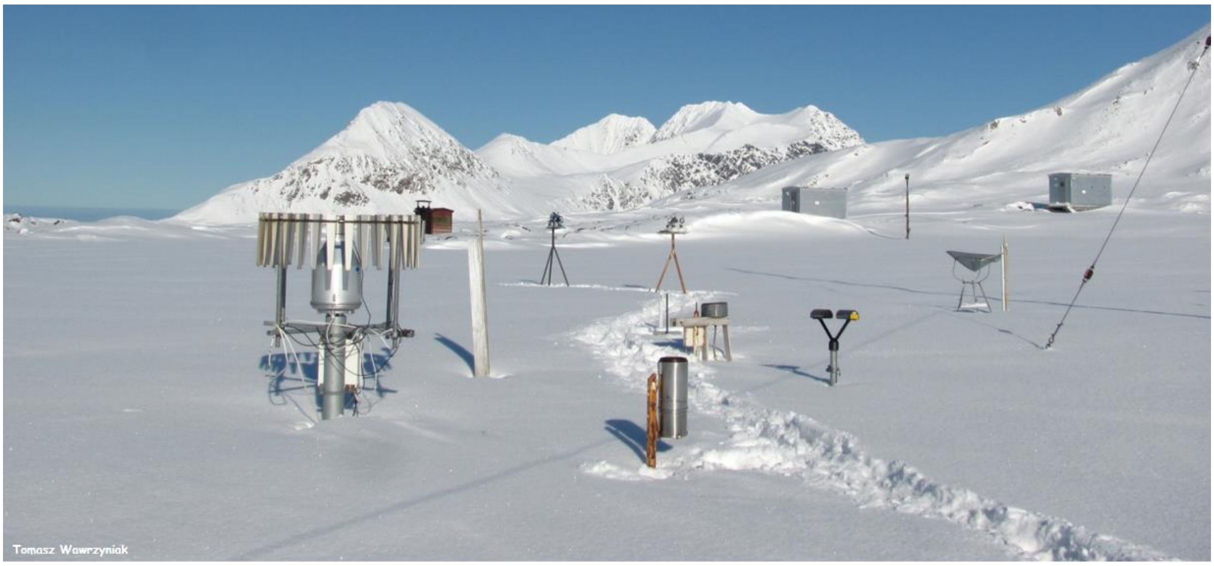


Figure 34. Polish Polar Station Hornsund meteorological site.

Hornsund is a modern interdisciplinary scientific platform that carries out research projects aimed at better understanding of the functioning of the arctic ecosystem and the changes it undergoes. The Atlantic sector of the Arctic has experienced the great temperature increase during the last three decades. Long term in situ measurements in the Arctic remain rare. Weather conditions are crucial factors that have a local feedback on many environmental components.

Meteorological variables collected at Hornsund help to characterize the climate variability in this part of the Arctic. Measured meteorological parameters, their time interval, and recent sensors are listed below:

- Air temperature, humidity, wind speed, wind direction, atmospheric pressure, dew point, solar radiation (3h interval since 1978, 1h since 2002, 1-minute interval since 2009) Sensors: HMP155, PTB330, WMT702, CMP11
- Precipitation rain gauges: Hellman (6h interval since 1978), Parsivel (since 2007), Geonor (since 2010), Present Weather Detector PWD52 (since 2016)
- Ground temperatures (up to 100 cm since 1978 and up to 12 m since 2017), sensors PT100 with QMT107
- Snow cover – manual point measurements (since 1982 daily), snow water equivalent (5-day intervals) and spatial distribution in the nearby catchment done weekly
- Observations every 3 hours since 1978: cloudiness, cloud types, cloud base (since 2017 ceilometer chm15k), visibility, significant weather

Statistical analysis of long time series indicate that significant positive trend of air temperature is visible for almost every day throughout the year. Only in March the trend in daily air temperature is insignificant (Fig. 35). The highest changes in precipitation are estimated from August to the first half of November, with peak up to 0.7 mm per day in decade at the turn of August and September (Fig. 36).

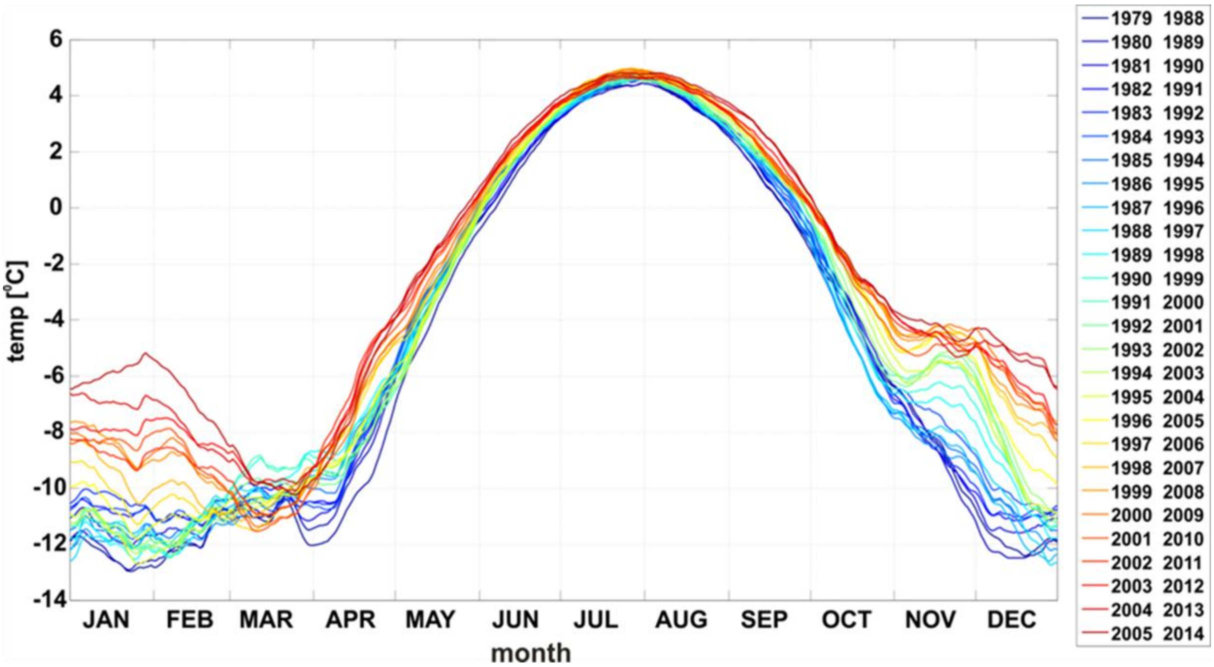


Figure 35. 10-year mean annual air temperature time series at Hornsund, using a one-year sliding averaging window, from 1979 to 2014. Original time series covers 36years, from 1979 to 2014, therefore, there are 27 10-year averages (Osuch and Wawrzyniak 2017).

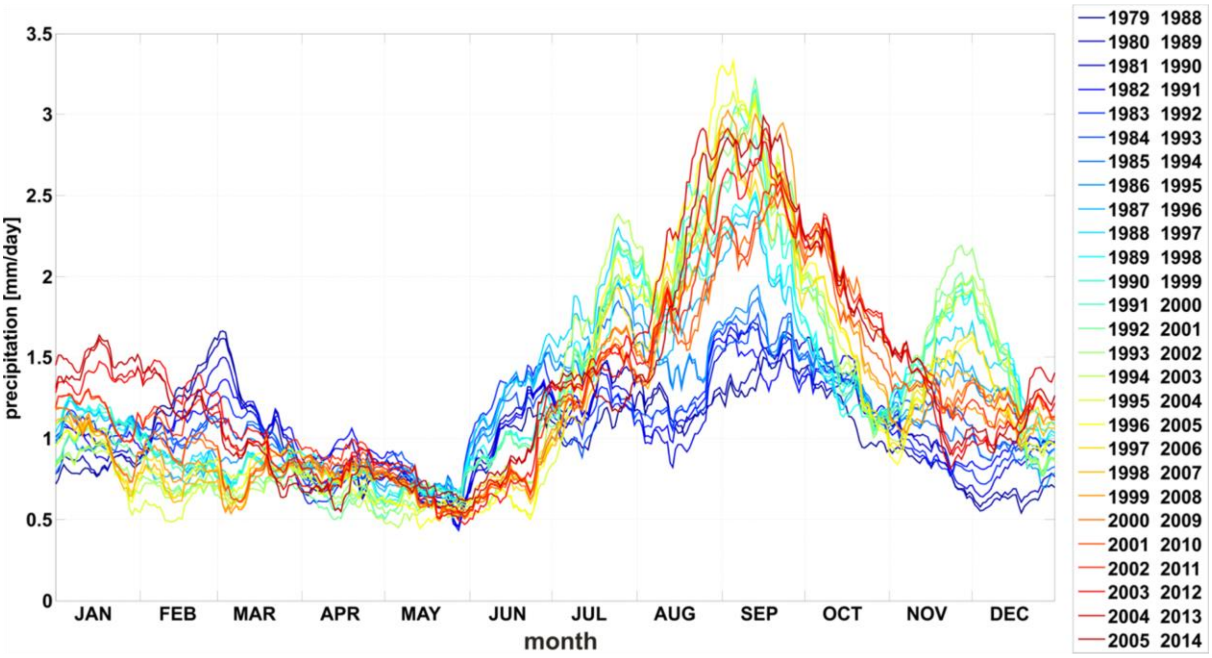


Figure 36. Same as Fig. 35 but for the daily sum of precipitation.

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 (Table 3). For instance, the requirement on spatial coverage of a network established to monitor a specific area (e.g. Greenland or Fram Strait) is defined on the basis of the spatial extension and representativeness needed to the network for the fulfilment of its goal. As a matter of fact, 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 also add to the assessment of the system.

Table 3. 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
Stable water isotopes	Climate research and monitoring, process studies	Pan-Arctic	> 20y time series for climate studies	Firm	Harald Sodemann	
IMR-PINRO Ecosystem Survey	Climate research and monitoring	Barents Sea (roughly from 68-82 N, 5-60 E)	> 20y time series for climate studies	Tentative	Geir Ottersen	
IMR Barents Sea Winter Survey	Climate research and monitoring	Barents Sea (roughly from 68-80 N,7-56 E)	> 20y time series for climate studies	Tentative	Geir Ottersen	
ASCOS/ ACSE	Scientific understanding: Central Arctic climate processes, boundary-layer processes & clouds	Entire Arctic Ocean	Continuous annual, multi-year	Firm	Michael Tjernström (MISU)	Set of comprehensive intensive observations during research cruise, including extensive cloud observations. Similar to land-based so-called “super-sites”.
NICE/ SeaState	Scientific understanding: Surface energy budget and atmospheric structure:	Entire Arctic Ocean	Continuous annual, multi-year	Firm	Michael Tjernström (MISU)	Set of intensive limited observations during research cruise, excluding extensive cloud observations. Similar to land-based observatories (e.g. IASOA etc.)
Polarstern	Atmospheric structure	Transect cruises; local within open ocean and sea ice	Monthly duration field campaigns during summer	Firm	Joseph Sedlar (MISU)	Complementary observations, taken on research cruises, regardless of science mission
Greenland Ecosystem Monitoring	Ecosystem monitoring and research	Greenland	> 20y time series for climate studies	Firm	Mikael Sejr (AU)	Quantifying ecosystem change in Greenland
PROMICE	Climate research and monitoring	Greenland ice sheet ablation zone	> 20y time series for climate studies	Tentative	GEUS	Determining the atmospheric near-surface climatology of the Greenland ice sheet ablation area
PROMICE	Global and regional NWP	Greenland ice sheet ablation zone	Continuous	Tentative	GEUS	Providing atmospheric near-surface parameters (e.g. atm pressure, air temp, relative humidity)
PROMICE	Research	Greenland ice sheet ablation zone	Continuous	Tentative	GEUS	Process understanding of the surface mass balance of the ice sheet ablation zone

GC-Net	Climate research and monitoring	Greenland ice sheet accumulation zone	>20y time series for climate studies.	Tentative	Konrad Steffen	Determining the atmospheric near-surface climatology of the Greenland ice sheet accumulation area
GC-Net	Global and regional NWP	Greenland ice sheet accumulation zone	Continuous	Tentative	Konrad Steffen	Providing atmospheric near-surface parameters (e.g. atm pressure, air temp, relative humidity)
GC-Net	Research	Greenland ice sheet accumulation zone	Continuous	Tentative	Konrad Steffen	Process understanding of the surface mass balance of the ice sheet accumulation zone
Radiosonde soundings	Global and regional NWP; Climate monitoring	Horizontal: Global (whole Arctic); Vertical: Through Troposphere and lower stratosphere	> 20y time series for climate studies, continuous	Firm	OSCAR	Most important user of radiosonde sounding data is numerical weather prediction. Sounding data can be found in the IGRA archive, and at most national weather services.
GAW programme	Climate research and monitoring	Gobal	> 20y time series for climate studies	Firm - tentative	Eija Asmi	Following WMO guidelines for different programs and parameters (confidence level depending on variable); include many data series older than establishment of official programme.
ICOS	Climate research and monitoring, Atmospheric composition for inverse modelling	Europe	> 20y time series for climate studies.	Firm	ICOS	Following WMO recommendation for compatibility of measurements of greenhouse gases and related tracers (GAW Report N°213), although this is now deprecated in the OSCAR database.
ACTRIS research infrastructure)	Climate research and monitoring	Europe	> 20y time series for climate studies.	Firm	Eija Asmi	Aerosols, clouds, trace gases in-situ ground-based and tower measurements infrastructure in Europe
FMI AWS	Meteorology	Finland	Continuous	Firm	Anna Kontu	Following WMO guidelines for meteorological measurements
FMI Snow depth stations	Meteorology/climate research	Cover the land types typical of the Arctic boreal forest, in an area of ~25 km^2	> 20y time series for climate studies.	Firm	Anna Kontu	Providing reference data for satellite cal/val purposes
GRUAN	Climate monitoring, satellite validation, process understanding	Global sparse	> 20y time series for climate studies.	Firm	DWD (GRUAN Lead Centre)	GRUAN not intended to be a globally dense network. Rather GRUAN acts as high-quality, metrologically traceable measurement series to enable other applications.
GOS Surface observations	Global and regional NWP; also Climate monitoring	Global (whole Arctic land surface)	Continuous	Firm	OSCAR	
Atmospheric tall tower network for greenhouse	Monitoring and research	pan-Arctic	> 20y time series for climate studies.	Tentative	Mathias Goeckede	Provide high-precision observations of atmospheric greenhouse gas mixing ratios, calibrated against WMO standards. Either continuous data, or episodic flask measurements.

gas monitoring						
NIVA Barents Sea Ferrybox	Monitoring and Research	Barents Sea Opening	> 20y time series for climate studies.	Tentative	Andrew King	Providing wind speed and hyperspectral radiance/irradiance measurements to assist marine biogeochemical studies
PEEX (Pan-Eurasian EXperiment)	Global/hemispheric/regional-scale modelling; Climate research and monitoring; Environmental assessment; Ecosystem research	Russian Arctic, north of 66.31°N	> 20y time series for climate studies.	Moderate	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 NWP, climate, ecosystem, etc. research; for data assimilation in operational forecasting and for models verification
Airborne atmospheric surface-flux measurements	Inverse emission modeling of atmospheric composition	Local at selected representative sites distributed circum-arctic	Biannual	Firm	Katrin Kohnert	Together with aircraft campaigns for flux measurements
Polish Polar Station Hornsund (WIGOS 01003)	Climate research and monitoring	Represent the terrestrial environment of an Arctic valley in North Atlantic sector of the Arctic, Hornsundfjord	> 20y time series for climate studies.	Firm	IGPAN (Tomasz Wawrzyniak, Piotr Głowacki)	Long term climate monitoring.

(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).

3.2 In situ and satellite-based data collections

Requirements for in-situ and satellite data collections are defined for data characteristics such as uncertainty and spatio-temporal coverage. While multiple sets of requirements for the same in situ data collection or satellite product can be defined, depending on application (e.g. climate, operational services, environmental protection, geo-hazard forecast, research development) and target levels (goal, breakthrough, and threshold), as in the collection of requirements in the WMO OSCAR database (https://www.wmo-sat.info/oscar/requirements), we are here synthesizing at a simpler level. Hence, when applicable the requirements, extracted from the OSCAR database and reported in Table 4, were merged into single sets of requirements for multiple applications, when refinement in OSACR was deemed unnecessary. For example, in the Arctic it is likely overkill to provide four different requirements for weather forecasting.

If OSCAR requirements are inapplicable (because not suitable for non-gridded data, or not tailored to the Arctic domain, or other reasons e.g. just missing), other requirements are described (Table 5). In any case, a comment to the OSCAR requirements is given in Table 4, discussing whether they are valid for the planned application or not.

Table 4. 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.	Obs. cycle	Timeliness	Spatial coverage	Conf Level	Comments
255, 256, 257	**Temperature**	Low Troposphere (LT) High Troposphere (HT), Low Stratosphere (LS)	NWP; Climate; Processes	0.5 K 1 K 3 K	25 km 100 km 300 km	LT: 0.1 km 0.2 km 0.5 km HT: 0.2 km 0.5 km 1.0 km LS: 1 km 2 km 3 km	60 min 3 h 6 h	10 min 1 h 3 h	Global	Firm	Horizontal resolution goal and breakthrough requirement are unrealistic for radiosonde sounding network. WMO No. 544 (Manual on the Global Observing System) define requirements for horizontal resolution of sounding networks, so that in densely populated areas the sounding stations should not be more than 250km apart and on sparsely populated areas the distance should not exceed 1000km. AIRS L3 global atmospheric temperature profiles meet breakthrough uncertainty level, and also breakthrough level in horizontal resolution. The vertical resolution of temperature profiles achieves the threshold level in the HT and LS but fail in LT. WMO No. 544 - Manual on the Global Observing System defines also the requirements for frequency of sounding, either 4 sounding a day at 00, 06, 12 and 18 UTC or at least 2 soundings per day at 00 and 12 UTC. The polar orbit of AIRS (12 h) fails to achieve the threshold level of observation cycle. Timeliness also fails to achieve the threshold level.
302, 303	**Specific humidity**	Low Troposphere (LT) High Troposphere (HT), Low Stratosphere (LS)	NWP; Climate; Processes	LT: 2 % 4 % 10 % HT, LS: 5% 10% 20%	LT & HT: 25 km 100 km 250 km LS: 50 km 150 km 300 km	LT: 0.1 km 0.2 km 0.5 km HT: 0.2 km 0.5 km 1.0 km LS: 1 km 2 km 3 km	60 min 6 h 12 h	10 min 1 h 3 h	Global	Firm	See general comment to 255, 256, 257. AIRS L3 global atmospheric specific humidity profiles meet the threshold uncertainty level. The threshold levels for horizontal resolution are met for the HT and LS, but the LT fails to meet the threshold level. The vertical resolution of specific humidity profiles achieves the threshold level in the HT and LS but fails in the LT. The polar orbit of the satellite (12 h) fails to achieve the threshold level of observation cycle. Timeliness meets the breakthrough level.
311, 312, 313	**Horizontal wind**	Low Troposphere/High Troposphere	NWP; Climate; Processes	1 m s^{-1} 3 m s^{-1} 5 m s^{-1}	25 km 100 km 500 km	0.3 km 1 km 3 km	60 min 6 h 12 h	6 min 30 min 6 h	Global	Firm	See general comment to 255, 256, 257 Uncertainty reaches threshold and possibly breakthrough, but no system reaches even threshold in spatial resolution, except possibly in some southern terrestrial parts of the Arctic
253, 338, 426	**Air temperature**	Near surface	NWP; Climate; Processes	0.1 K 0.5 K 1 K	10 km 20 km 50 km	N/A	10 min 1 h 3 h	10 min 1 h 3 h	Global	Firm	Uncertainty reaches threshold and possibly locally breakthrough levels. Threshold level resolution only reached locally on land, usually not; especially not over Arctic Ocean.

252, 337	**Air specific humidity**	Near surface	NWP; Climate; Processes	2 % 5 % 10 %	10 km 20 km 50 km	N/A	10 min 1 h 3 h	10 min 30 min 3 h	Global	Reasonable	Uncertainty reaches threshold and possibly locally breakthrough levels. Threshold level resolution only reached locally on land, usually not; especially not over Arctic Ocean. Technical limitations causes malfunctions
318, 319, 389, 390, 445, 446	**Wind speed**	Near surface	NWP; Climate; Processes	0.5 m/s 1 m/s 3 m/s	15 km 100 km 250 km	N/A	10 min 1 h 3 h	10 min 30 min 3 h	Global	Firm	Uncertainty reaches threshold and possibly locally breakthrough levels. Threshold level resolution only reached locally on land, usually not; especially not over Arctic Ocean. Representatively set lower limits on horizontal resolution, especially in complex terrain.
250, 251, 335, 488, 487	**Air pressure**	Near Surface	NWP; Climate; Processes	0.5 hPa 1 hPa 1 hPa	10 km 20 km 50 km	N/A	10 min 1 h 3 h	10 min 30 min 3 h	Global	Firm	Uncertainty reaches threshold, breakthrough and often target levels. Horizontal resolution reaches threshold level only locally and only on land.
244	**Accumulated precipitation**	Near surface	NWP; Climate; Processes	0.5 mm 2 mm 5 mm	10 km 30 km 100 km	N/A	10 min 1 h 3 h	19min 1 d 3 h	Global	Firm	Uncertainty pertains to 24-hour accumulation.
274, 701, 93	**Downward short-wave irradiance**	Near Surface	NWP; Climate; Processes	1 W m^{-2} 10 W m^{-2} 20 W m^{-2}	5 km 20 km 50 km	N/A	10 min 1 h 5 h	24 h 5 d 30 d	Global	Reasonable	Spatial coverage requirement refer to satellite product, not applicable to single-point data. Uncertainty achieves the breakthrough level. The goal level is exceeded for all other requirements.
358, 662, 700	**Surface albedo**	Surface	NWP; Climate; Processes	5 % 10 % 20 %	1 km 2 km 10 km	N/A	1 h 2 h 6 h	24 h 5 d 30 d	Global	Reasonable	Spatial coverage may refer to satellite derived product and is not applicable to point data from surface stations.
275, 702, 95	**Downward long-wave irradiance**	Near Surface	NWP; Climate; Processes	1 W m^{-2} 10 W m^{-2} 20 W m^{-2}	5 km 20 km 50 km	N/A	10 min 1 h 6 h	24 h 5 d 30 d	Global	Reasonable	Spatial coverage may refer to satellite derived product and is not applicable to point data from surface stations. Uncertainty achieves the breakthrough level. The goal level is exceeded for all other requirements.
118, 308	**Upward long-wave irradiance**	Near Surface	NWP; Climate; Processes	1 W m^{-2} 10 W m^{-2} 20 W m^{-2}	10 km 30 km 100 km	N/A	60 min 3 h 6 h	24 h 5 d 30 d	Global	Reasonable	Spatial coverage may refer to satellite derived product and is not applicable to point data from surface stations.
259, 343, 430, 703, 81	**Cloud fraction**	Total column	NWP, Nowcasting & Climate	5 % 10 % 20 %	1 km 5 km 20 km	N/A	10 min 1 h min 6 h	24 h 5 d 30 d	Global	Tentative	Spatial coverage may refer to satellite derived product and is not applicable to point data from surface stations. The goal level is exceeded for all requirements.
345, 346	**Ice water content**	Tropospheric column, profile	NWP, Nowcasting & Climate	5 % 8 % 20 %	0.5 km 2 km 10 km	0.1 km 0.17 km 0.5 km	15 min 60 min 3 h	15 min 30 min 2 h	Global	Firm	Uncertainty does not meet the threshold level. The goal level is exceeded for all other requirements. However ice water content profiles are valid for zenith only and therefore lacks the spatial component.
350	**Liquid water path**	Total column	NWP, Nowcasting & Climate	10 g m^{-2} 20 g m^{-2} 50 g m^{-2}	0.5 km 2 km 10 km	N/A	15 min 60 min 3 h	15 min 30 min 2 h	Global	Speculative	Uncertainty achieves the breakthrough for surface-based radiometry. The goal level is exceeded for all other requirements. Surface-based liquid water path measurements are valid for zenith only as a point measurement, and therefore lacks the spatial component. Satellite observations include spatial component but reaches only threshold in summer, but not in winter.

114, 115, 204, 380, 449	**Integrated water vapor**	Total column	NWP, Nowcasting & Climate	1 kg m^{-2} 2 kg m^{-2} 5 g m^{-2}	1 km 5 km 50 km	N/A	30 min 1 h 3 h	30 min 1 h 3 h	Global	Reasonable	
304	**Integrated Water Vapour (IWV)**	Total column	Global NWP	1 kg.m^{-2} 2 kg.m^{-2} 5 kg.m^{-2}	15 km 50 km 250 km	N/A	1 h 6 h 12 h	6 min 30 min 6 h	Global	Firm	By John Eyre 2009. Hi Res NWP equal uncertainties, but higher Horiz. res., Os cycle and Timeliness which UB's product cannot achieve.

Table 5. Non-OSCAR requirements for the in-situ and satellite-based data collections

Variable name	**Layers**	**App. area**	**Uncert.**	**Horiz. res.**	**Vert. res.**	**Os cycle**	**Timeliness**	**Spatial overage**	**Conf Level (1)**	**Source (name or reference to literature)**	**Comments**
Air temperature	Atmospheric boundary layer	Processes, Research	0.1 K 0.5 K 1 K	N/A	5 m 10 m 15 m	Irregular; field campaign	1 month 2 months 3 months	Circum-arctic (One area per arctic region)	firm	Katrin Kohnert (GFZ)	Uncertainty should be lower than in Table 4 since the vertical gradient needs to be known
Water vapour concentration	Atmospheric boundary layer			-	5 m 10 m 15 m	-	1 month 2 months 3 months	Circum-arctic (One area per arctic region)	firm	Katrin Kohnert (GFZ)	
Air pressure	Atmospheric boundary layer		0.5hPa 1 hPa 1 hPa	-	5 m 10 m 15 m	-	1 month 2 months 3 months	Circum-arctic (One area per arctic region)	firm	Katrin Kohnert (GFZ)	See comments for above; vertical resolution critical
CH4 concentration	Atmospheric boundary layer			-	5 m 10 m 15 m	-	1 month 2 months 3 months	Circum-arctic (One area per arctic region)	firm	Katrin Kohnert (GFZ)	Has several OSCAR ID numbers, but all are out of date
CO2 concentration	Atmospheric boundary layer			-	5 m 10 m 15 m	-	1 month 2 months 3 months	Circum-arctic (One area per arctic region)	firm	Katrin Kohnert (GFZ)	
Water vapour isotope HDO	Boundary layer, free troposphere	Global NWP, Climate	0.5 permil	500 km		-	1 month	European arctic	moderate	Sodeman	Has OSCAR ID 78, however, without requirements. For station observations
Water vapour isotope H218O	Boundary layer, free troposphere	Global NWP, Climate	2 permil	500 km		-	1 month	European arctic	Moderate	Sodeman	For station observations
Turbulent sensible heat flux	Near surface		2 W m^{-2} 5 W m^{-2} 15 W m^{-2}			5 min 20 min 60 min	30 days 60 days 200 days	Point measurements		Sedlar, MISU	Averaging time required limits temporal resolution

Turbulent latent heat flux	Near surface		2 W m^{-2} 5 W m^{-2} 15 W m^{-2}			5 min 20 min 60 min	30 days 60 days 200 days	Point measurements		Sedlar, MISU	Averaging time required limits temporal resolution
Turbulent momentum flux	Near surface		1 m^2 s^{-2} 2 m^2 s^{-2} 5 m^2 s^{-2}			5 min 20 min 60 min	30 days 60 days 200 days	Point measurements		Sedlar, MISU	Averaging time required limits temporal resolution
Cloud top pressure	Highest present	Climate	50 hPa 100 hPa 20 hPa	0.25 deg		12 hr		Global	Firm	Devasthale, SMHI	CM-SA CLARA-A2 satellite dataset, validation report Requirements on accuracy, precision and stability per decade resp.
Cloud top height	Highest present	Climate	800 m 1700 m 200 m	0,25 deg		12 hr		Global	Firm	Devasthale, SMHI	CM-SA CLARA-A2 satellite dataset, validation report Requirements on accuracy, precision and stability per decade resp.
Cloud ice water path	Total column	Climate	20 gm^2 40 gm^2 6 gm^2	0.25 deg		24 hr		Global	Firm	Devasthale, SMHI	CM-SA CLARA-A2 satellite dataset, validation report Requirements on accuracy, precision and stability per decade resp.
Aerosol in-situ parameters: scattering and absorption, aerosol number, mass and size distribution	Near surface	Climate Applications and Air Quality	10% 20% 30%			5 min 30 min 1 h	5 min 30 min 1 h	Global	Tentative	Eija Asmi	The goal of the Global Atmosphere Watch (GAW) programme is to ensure long-term measurements in order to detect trends in global distributions of chemical constituents in air and the reasons for them. With respect to aerosols, the objective of GAW is to determine the spatio-temporal distribution of aerosol properties related to climate forcing and air quality on multi-decadal time scales and on regional, hemispheric and global spatial scales.
Relative humidity	Near surface	Climate research and monitoring	2 % 5 % 10 %			60 min 3 h 12 h	6 min 30 min 6 h	Global	Tentative	Eija Asmi	Based on OSCAR requirements for near-surface spec. humidity for Global NWP (ID 252), but excluding the horizontal resolution requirement as the station-based measurements cannot deliver the satellite-level of coverage stated in OSCAR.
Aerosol absorption coefficient	Near surface	Climate Applications and Air Quality	10% 20% 30%	1000 km		5 min 30 min 1 h	60 min 1d 1 y	Global	tentative	Eija Asmi	“With respect to aerosols, the objective of GAW is to determine the spatio-temporal distribution of aerosol properties related to climate forcing and air quality on multi-decadal time scales and on regional, hemispheric and global spatial scales.”

Hydrometeor classification		Global NWP and Climate applications			10 m 100 m	30 sec 3 min 1 h	5 min 1 h 1 d	Global	tentative	Ewan O'Connor	NWP/Climate model evaluation and assimilation: uncertainties and vertical resolution suitable. For NWP assimilation, timeliness potentially achievable for many stations. Horizontal coverage not realistically achievable, especially over ocean/ice.

(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 6. The variables addressed in this assessment report are underlined.

Table 6. Atmosphere in situ observing systems

Network or System	Relevant variables	Data assessor	Data Centres and Archives	Coordinating Bodies
AC-AHC2 stable water isotope measurement stations	● H216O ● HDO ● H218O	Harald Sodemann (UiB)	CNRS-LSCE (Valerie Masson-Delmotte); AWI (Martin Werner)	CNRS-LSCE
IMR-PINRO Ecosystem Survey	● Wind speed and direction	Geir Ottersen (IMR)		
IMR Barents Sea Winter Survey	● Wind speed and direction	Geir Ottersen (IMR)	Norwegian Marine Data Centre (NMDC)	
Atmospheric observations collected during field campaigns (campaigns including extensive atmospheric observations, in addition to synoptic observations)	● Air temperature ● Wind speed and direction ● Water vapour ● Temperature, water vapor and wind from soundings ● Pressure ● Precipitation ● Surface energy budget (turbulent and radiation fluxes) ● Cloud properties	Michael Tjernström and Joe Sedlar (MISU)	● https://bolin.su.se/data/?c=atmosphere ● http://www.npolar.no/en/projects/n-ice2015.html ● http://www.apl.washington.edu/project/project.php?id=arctic_sea_state ● https://www.pangaea.de/	MISU NPI ONR AWI

Greenland Ecosystem Monitoring Programme	• Air temperature • Relative humidity • Wind speed and direction • Shortwave radiation budget • Precipitation • Atmospheric pressure • Snow cover • CO2 and CH4 flux	Mikael Sejr (AU)	• http://zackenberg.dk/data/ • http://data.g-e-m.dk/	GEM
PROMICE Automatic weather station network	• Air temperature • Relative humidity • Wind speed and direction • Shortwave radiation budget • Longwave radiation budget • Air pressure	Andreas Ahlstrøm (GEUS)	• https://promice.org/DataDownload.html	GEUS
Greenland Climate Network	• Air temperature • Relative humidity • Wind speed and direction • Shortwave radiation budget • Longwave radiation budget • Air pressure	Andreas Ahlstrøm (GEUS)	• http://cires1.colorado.edu/steffen/gcnet/	CIRES
Radiosounding network in the Arctic (inside the AMAP geographical boundaries) and IGRA	• Upper-Air temperature • Upper-Air Wind speed and direction • Upper-Air Water vapour	Tuomas Naakka (FMI) Joe Sedlar (MISU)	• https://public.wmo.int/en/programmes/global-observing-system • https://www.ncdc.noaa.gov/data-access/weather-balloon/integrated-global-radiosonde-archive	GCOS NOAA
Global GAW inside the AMAP geographical boundaries	• Surface and Upper-Air temperature • Surface and Upper-Air Wind speed and direction • Surface and Upper-Air Water vapour • Pressure • Precipitation • Surface radiation budget • Carbon dioxide • Methane • and other long-lived greenhouse gases • Ozone and Aerosols • Cloud properties	Ewan O'Connor (FMI)	• IASOA Data Portal: https://www.esrl.noaa.gov/psd/iasoa/dataataglance • ACTRIS Data Portal: http://actris.nilu.no • EBAS Data Portal (World Data Centre for Aerosol, WDCA; World Data Centre for Reactive Gases, WDCRG) http://ebas.nilu.no • World Ozone and UV radiation Data Centre (WOUDC), https://woudc.org/	WMO
Regional GAW inside the AMAP geographical boundaries	• Surface and Upper-Air temperature • Surface and Upper-Air Wind speed and direction • Surface and Upper-Air Water vapour • Pressure • Precipitation • Surface radiation budget • Carbon dioxide	Ewan O'Connor (FMI)	• IASOA Data Portal: https://www.esrl.noaa.gov/psd/iasoa/dataataglance • ACTRIS Data Portal: http://actris.nilu.no • EBAS Data Portal (WDCA, WDCRG) http://ebas.nilu.no • WOUDC, https://woudc.org/	WMO

	• Methane • and other long-lived greenhouse gases • Ozone and Aerosols • Cloud properties			
ICOS inside the AMAP geographical boundaries	• Carbon dioxide • Methane • Other long-lived greenhouse gases • Water vapour	Ewan O'Connor (FMI)	• ICOS Carbon Portal https://data.icos-cp.eu/	
ACTRIS cloud properties inside the AMAP geographical boundaries	• Cloud boundaries • Cloud fraction • Cloud liquid water content • Cloud ice water content • Liquid water path	Ewan O'Connor (FMI)	• ACTRIS Data Portal: http://actris.nilu.no	ACTRIS
FMI AWS	• Air temperature • Precipitation • Other meteorological parameters	Anna Kontu (FMI)	• http://litdb.fmi.fi/	FMI
FMI Snow depth stations	• Air temperature	Anna Kontu (FMI)	• http://litdb.fmi.fi/	FMI
GCOS Reference Upper-Air Network (GRUAN) inside the AMAP geographical boundaries	• Upper-air temperature • Upper-air humidity • Upper-air winds	Peter Thorne (NUIM)	• https://www.gruan.org/	GCOS
GOS surface stations	• Surface temperature • Surface humidity • Precipitation • Snow cover • Surface pressure • Surface winds • Various ancillary	Peter Thorne (NUIM)	Pending	C3S
Tower network for atmospheric trace gas mixing-ratio monitoring (e.g. CO2, CH4, N2O,. ..), or GCOS-affiliated WMO/GAW Global Atmospheric monitoring network	• Temperature • Humidity • Wind • Carbon dioxide • Methane • and other long-lived greenhouse gases • Snow cover	Mathias Goeckede (MPG)	• GAW world data centers (from GAWSIS) https://gawsis.meteoswiss.ch/GAWSIS//index.html#/ • EMEP (http://ebas.nilu.no/default.aspx) for Aerosol and met (for the Arctic: AMAP network, CAMP network, MOCA (Norway, Ny Alesund), NILU (Norway, Lapland+Svalbard), ROSHYDROMET • WDCGG (World Data Centre for Greenhouse Gases) changing to WDCRG (World Data Centre for Reactive Gases)	
NIVA Barents Sea FerryBox	• wind speed and direction • hyperspectral radiance/irradiance	Andrew King, Kai Sørensen,	https://www.niva.no/en/water-data-on-the-web/ferrybox-ships-of-opportunity	NIVA

		Pierre Jaccard (NIVA)		
Pan-Eurasian Experiment (PEEX) (https://www.atm.helsinki.fi/peex/index.php)	• Surface air temperature • Surface wind speed and direction • Surface relative humidity • Precipitation	Hanna Lappalainen & Alexander Mahura (UHEL)	PEEX atmosphere observing system metadata: https://peexdata.atm.helsinki.fi/;Data collections are available on request from owners	PEEX
Airborne observations of surface-atmosphere fluxes	• Carbon dioxide • Methane • Water vapour • Air temperature • Wind speed and direction	Katrin Kohnert, Andrei Serafimovich, Torsten Sachs (GFZ)		GFZ and AWI
Polish Polar Station Hornsund (WIGOS 01003)	• Air temperature, • Wind speed and direction, • Water vapor, • Atmospheric pressure, • Precipitation • other meteorological variables	Tomasz Wawrzyniak, Piotr Głowacki (IGPAN)	https://hornsund.igf.edu.pl/en/	IGPAN

According to the respondents to the survey, 16 out of the 24 addressed in situ atmospheric observing systems do not have any risk of negative impact on the environment. For the other 8 atmospheric 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). The results are illustrated in Table 7.

In the case of Sodankylä supersite, reindeers have sometimes stuck to the cabling of the measurement system. In Sodankylä and in the other sites where radiosondes are launched (Radiosounding network in the Arctic; field campaigns such as ASCOS, ACSE, and N-ICE2015; Polarstern cruises) radiosondes are never or rarely retrieved, with the consequent release of plastic (lattice) balloons and lithium ion batteries on land or into the ocean. The NIVA Barents Sea FerryBox observing system is on a ship of opportunity that is operating regardless of whether the observing system is on board. While the observing system itself does not have a negative impact on the environment, the supporting platform (the ship) does have a negative impact (fuel use and combustion emissions, some ballast water transport probably?). Similar impact is present in the case of ship-based measurement campaigns (ASCOS, ACSE, Polarstern). This is a gray area that can be interpreted in different ways. In the case of the Global Observing System (surface synoptic measurements), its possible impacts on the environment are related to the release of the mercury present in glass thermometers and some other instrumentation if not properly handled.

Table 7. 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. In case of doubt, the indicators are marked in yellow.

Indicators of good environmental status	**Observing system**							
	Sodankylä supersite	**Radiosounding network in the Arctic**	**ASCOS; ACSE**	**Polarstern Arctic field campaigns**	**N-ICE2015**	**NIVA Barents Sea FerryBox**	**GRUAN**	**Global Observing System (surface synoptic meas.)**
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)	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
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)	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
The observing system does not affect the health of the population of commercially relevant animals (insects, birds, mammals, fishes)	🟥	🟩	🟩	🟩	🟩	🟩	🟩	🟩
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)	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
Eutrophication introduced by the observing system in the nearby water bodies is minimized (especially adverse effects thereof, such as losses in biodiversity, ecosystem degradation, harmful algae blooms and oxygen deficiency in bottom waters)	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
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)	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
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 (by energy, we mean heat, noise, electromagnetic radiation, radio waves or vibrations)	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

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 8 and 9 describes the spatial and temporal observation gaps, respectively.

Table 8. Spatial coverage

Observing system	Spatial coverage of the observing system	Required spatial coverage	Comparison: observed vs required
AC-AHC2 stable water isotope measurement stations	European Arctic	pan-Arctic	Storm systems transport water vapour far into the Arctic, beyond the European Arctic region. To identify the processing of moisture during storms entering the Arctic through the North Atlantic and Pacific storm track, stations in eastern Scandinavia constitute a large gap. In Russia, only a small part of Siberia is covered with isotope measurements. Measurements in the northern parts of Canada are also currently absent.
IMR-PINRO Ecosystem Survey	Barents Sea (northern part often not covered)	Barents Sea (the whole)	The purpose of the survey is to cover area with main fish species. As the ice has retreated and cod and haddock expanded northwards cruise now covers larger area. The coverage is adequate for this purpose and the meteorological data comes as a spin-off.
IMR Barents Sea Winter Survey	Barents Sea (northern part often not covered)	Barents Sea (the whole)	The purpose of the survey is to cover area with main fish species. As the ice has retreated and cod and haddock expanded northwards cruise now covers larger area. The coverage is adequate for this purpose and the meteorological data comes as a spin-off.
Arctic Summer Cloud Ocean Study (ASCOS) field campaign	Sea-ice based in situ field campaign	Entire Arctic Ocean	Intensive, short duration scientific field campaign focused on a local, central observatory based on the floating sea ice. Such experiments target understanding and should cover different regimes, hence the “whole Arctic” but spatial resolution is not critical. A general lack of such work, especially during the off-melt seasons means it does not meet requirements.
Arctic Clouds during Summer Experiment (ACSE) in situ field campaign	Icebreaker based in situ field campaign Arctic Ocean transect	Entire Arctic Ocean	See ASCOS, above.
Norwegian Young Sea Ice Cruise 2015 (N-ICE2015)	Sea-ice based in situ field campaign	Entire Arctic Ocean	See ASCOS, above.
Sea State 2015 in situ field campaign	Icebreaker based in situ field campaign	Entire Arctic Ocean	See ASCOS, above.
Polarstern in situ field campaigns	Icebreaker based in situ field campaigns	Entire Arctic Ocean	Series of intensive, short duration scientific field campaigns focused on a local, central observatory based on the icebreaker Polarstern. Operational soundings performed during

			otherwise non-meteorological expeditions add value, but is insufficient to meet spatial coverage requirements.
Greenland Ecosystem Monitoring Programme	Point measurements	Local scale, coastal Greenland	The purpose of the programme is to observe the ecological implication of physical change. This is currently successfully obtained at two sites and will be expanded by a third site in 2018. Basic meteorology is a spin-off.
PROMICE Automatic weather stations network	Point measurements mainly in the melt (ablation) zone of the Greenland ice sheet placed in different regions in Greenland	Requirements on spatial density of stations depend on the meteorological parameter considered. Generally, 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 and/or financial reasons.
Greenland Climate Network	Point measurements mainly in the accumulation zone of the Greenland ice sheet placed in different regions in Greenland	Requirements on spatial density of stations would depend on the meteorological parameter considered. Generally, regions in Greenland with different climate should be covered to represent spatial variability	Currently, SW Greenland is an important region, yet under-represented.
Radiosounding network in the Arctic	Land areas including few small island	Whole Arctic	Network of radiosounding is sparse in the Arctic but covers the most of land areas and the stations situated on island enlarge coverage also over Ocean, but no permanent radiosounding station are situated in the central Arctic Ocean.
Global & regional GAW inside the AMAP geographical boundaries	Global, including 47 Regional and 4 Global stations in the Arctic	Arctic including land and ocean areas	Over 50 stations in the Arctic coastal and continental areas. Central Arctic still under-represented geographically. Most stations measure only view parameters which is not sufficient to monitor the atmospheric composition state.
ICOS	Europe (including European Arctic), point measurements and ocean cruises	Pan-Arctic	Insufficient; much of the Arctic still under-represented

ACTRIS	Europe	Arctic	ACTRIS focused in Europe - only 3 stations inside the AMAP boundaries is insufficient to meet the requirements.
FMI AWS	Finland	Finland	The measurement sites capture the variability of the near surface atmospheric variables across Finland
FMI snow depth stations	Point measurements over different surface types (grass field, forest, bog)	Cover the land types typical of the Arctic boreal forest, in an area of ~25 km^2	The requirement is fulfilled
GRUAN	3 point observations (Barrow, Ny Ålesund, Sodankyla)	N/A (no spatial requirements for reference networks)	N/A. For satellite comparisons D1.1 from GAIA-CLIM suggests coverage is adequate for purpose, but more climate zones would be beneficial (http://www.gaia-clim.eu/sites/www.gaia-clim.eu/files/document/d1.11_final.pdf)
Surface meteorological holdings (GOS)	Arctic domain land	WMO OSCAR Surface requirements (Table 4)	Variable dependent but generally between threshold and not met within the arctic domain as a whole. See Fig. 28.
Tower network for atmospheric trace gas mixing-ratio monitoring	pan-Arctic	pan-Arctic	Since tall tower footprints are large and vary with wind climatology, without further analyses of atmospheric transport gaps cannot be quantified. Based on the current distribution of sites, the European Arctic and Alaska are comparatively well covered, while the eastern part of Siberia features the largest gaps.
NIVA Ferrybox	Barents Sea opening between Tromsø and Longyearbyen	N/A This is a ship of opportunity line	The FerryBox is on a ship of opportunity that voluntarily permits scientific equipment to travel with the ship. The route may change without much advanced warning and cooperation is also dependent on the relationship between scientist and the shipping company. Increased spatial coverage by increasing the number of ships of opportunity operating in the Arctic would of course be welcome to the observing system.
PEEX (Pan-Eurasian EXperiment)	Arctic regions of Russia (northerly of 66.31N)	Sparse voluntary network.	Although stations are placed within the tundra environment, these are spaced at large distances from each other along the longitudinal belt. Increased number of stations with an enlarged programme of measurements would be desirable for a more densely spatial coverage of the Russian Arctic. An optimization task for calculating geographical positioning would be useful in order to have larger number of representative stations.
Airborne observations of surface-atmosphere fluxes	Representative regions across the whole Arctic	One study area in each mayor arctic zone (Alaska, Canada, Russia, Europe)	Unclear how many regions that would be required for a proper representation of fluxes of the whole terrestrial Arctic. European Arctic is lacking.

Polish Polar Station Hornsund (WIGOS 01003)	Local single station	Local conditions of Hornsundsfjord, hopefully representative for Southern Spitsbergen.	This station represents rather local conditions of western part of Hornsundsfjorden, at the marine terrace but there are significant topoclimatic differences dependent on height above sea level, substrate type, distance from the sea, exposition, atmospheric circulation and the ice conditions.

Table 9. Temporal coverage (temporal extension and breaks of the system's data collections)

Observing system	Temporal coverage of the observing system	Required temporal coverage	Comparison: observed vs required
AC-AHC2 stable water isotope measurement stations	Measurements starting and ending at different periods since 2011	Continuous observations	Continuation of measurements at key sites (Svalbard, Iceland) not guaranteed; time series short for climate.
IMR-PINRO Ecosystem Survey	Annually in August-September since 2004	> 20y time series for climate studies.	The purpose of the survey is to cover area with main fish species. The coverage is adequate for this purpose. For measuring wind coverage should be more frequent.
IMR Barents Sea Winter Survey	Annually in January-February 1976- ongoing	> 20y time series for climate studies.	The purpose of the survey is to cover area with main fish species. The coverage is adequate for this purpose. For measuring wind coverage should be more often.
Arctic Summer Cloud Ocean Study (ASCOS) in situ field campaign	August - September 2008	Continuous observations	During field campaigns the temporal resolution is high. Requirement of continuous observation will not be fulfilled by in situ field campaigns. Especially observations in the non-melt season are lacking.
Arctic Clouds during Summer Experiment (ACSE) field campaign	July - October 2011	Continuous observations	This campaign captured freeze-up; else see ASCOS comment above
Norwegian Young Sea Ice Cruise 2015 (N-ICE2015)	January - June 2015	Continuous observations	This is a unique winter campaign; else see ASCOS comment above
Sea State 2015 field campaign	October - November 2015	Continuous observations	This campaign captured freeze-up; else see ASCOS comment above
Polarstern field campaigns	June to October for years: 2007, 2008, 2009, 2010, 2011, 2012, 2014	Continuous observations	Polarstern has capacity to perform meteorological observations, especially soundings, also during non-atmospheric expedition. Else, see ASCOS comment above.
Greenland Ecosystem Monitoring Programme	The full programme including all sub-programmes was initiated in 2007	>20y time series for climate studies. Continuous operation	Aimed to guarantee sustainable long-term operation and quality assurance. Yet short time series for climate.
PROMICE Automatic weather stations network	Main network operational since 2010. Measurement every 10 min but with low transmission rate, especially in winter	Duration indefinite. Measurement frequency 10 m. Transmission rates should be at least once an hour	In terms of duration, the AWS should be maintained indefinitely to follow decadal trends in climate variability. In terms of observation frequency, it depends on the meteorological parameter considered, but the current 10 minute rate seems adequate. Generally, the transmission rate should be increased

			especially in the wintertime to obtain uniform transmission rates throughout the year with hourly transmissions as a feasible goal.
Greenland Climate Network	Most of network operational since 1997. Measurement frequency is 1 min with substantially lower data transmission rate, especially in winter	Duration indefinite. Measurement frequency of 10 m generally satisfies requirements of most parameters. Transmission rates should be at least once an hour	In terms of duration, the AWS should be maintained indefinitely to follow decadal trends in climate variability. In terms of observation frequency, it depends on the meteorological parameter considered, but the current 1 minute rate seems adequate. Generally, the transmission rate should be maintained at hourly transmissions all year as a minimum.
Radiosounding network in the Arctic	Most stations established in 1940s or -50s, some stations have been closed; breaks in observations occur. Observations typically once or twice daily	> 20y time series for climate studies. Continuous observation with at least two soundings per day.	The requirement of continuous observation is not fulfilled for every stations. Frequency is not always fulfilled
Global & regional GAW inside the AMAP geographical boundaries	Established in 1989 - however many data series (e.g. ozone) are much longer	> 20y time series for climate studies. Continuous operation	In theory, continuous observations. However, funding not guaranteed and many data series have gaps and stations have been closed.
ICOS	Continuous coverage for land sites, starting as early as 2001, not continuous for ocean.	> 20y time series for climate studies. Continuous coverage	Aimed to guarantee sustainable long-term operation and quality assurance.
ACTRIS	Start in 2014 but still in in establishment phase	Continuous observations	Aimed to guarantee sustainable long-term operation and quality assurance. High-rate but point measurements.
FMI AWS	Daily or synoptic (see panels of Fig. 28)	Continuous observations	Generally met as requirement is synoptic reporting.
FMI snow depth stations	2006-ongoing	Continuous observations	Data available at 10 min intervals. Before 2006 daily manual measurements

GRUAN	Daily to 4-times daily radiosonde ascents	Minimum requirement is weekly per GRUAN manual	Exceeded
Surface meteorological holdings (GOS)	Daily or synoptic (see panels of Fig. 28)	Continuous observations	Generally met as requirement is synoptic reporting, but stations closures is a problem.
Tower network for atmospheric trace gas mixing-ratio monitoring	Continuous measurements, starting as early as 1971	> 20y time series for climate studies. Continuous operation	The temporal coverage of the existing systems is adequate
NIVA Ferrybox	~25 round trips between Tromsø and Longyearbyen since 2008	> 20y time series for climate studies. Continuous operation	Temporal coverage meets about 40% of requirement
PEEX (Pan-Eurasian EXperiment)	Earliest start (among 11 stations) 1930 at Igarka GeoCryLab; measurements are performed at 6 h intervals	Continuation of observations needed; time interval 3 hourly	Duration relatively short at 4 measurement stations (Seida Vorkuta, Kashin, Belyy, Heiss Island, from 2007, 2008, 2009, 2010, respectively); insufficient for climate related studies; observations performed at every 3 h interval would desirable, especially for NWP community.
Airborne observations of surface-atmosphere fluxes	2012.06 - 2012.08, 2013.07, 2014.04 – 2014.08, and 2016.08 – 2016.09	20 years with flights at least every second year (including spring/autumn campaigns)	Alaska, Canada and Russia flight campaigns started in 2012 with some repetitions since, but repetition of Russia campaigns is still limited. The profile flights are coupled to flux measurement campaigns that define the temporal coverage requirement.
Polish Polar Station Hornsund (WIGOS 01003)	1978 - ongoing	> 20y time series for climate studies	Temporal coverage meets requirement

4.1.3 Gaps in the observation variables

In Table 10 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 such as sensible and latent heat fluxes that are relevant for various research and operational applications.

Table 10. Essential variables measured by the in situ observing systems

Atmospheric domain	**Essential Variable**	**Observing systems measuring the essential variables**
SURFACE	Air temperature	• Polish Polar Station Hornsund (WIGOS 01003)Greenland Ecosystem Monitoring program • Global-GAW • Regional GAW • ICOS • Sodankylä supersite (FMI) • PROMICE automatic weather station network • Greenland Climate Network (GC-Net) • IMR-PINRO Ecosystem Survey • IMR Barents Sea Winter Survey • Field experiments: Arctic Summer Cloud Ocean Study (ASCOS); Arctic Clouds during Summer Experiment (ACSE); Norwegian Young Sea Ice Cruise 2015 (N-ICE2015); Sea State 2015. • Global Observing System (GOS; surface synoptic measurements) • Svalbard Automated Weather and Snow Measuring System • PEEX (Pan-Eurasian Experiment) • Svalbard Automated Weather and Snow Measuring System
	Wind speed and direction	• Polish Polar Station Hornsund (WIGOS 01003) • Greenland Ecosystem Monitoring program • Global and Regional GAW • ICOS • Sodankylä supersite (FMI) • PROMICE automatic weather station network • Greenland Climate Network (GC-Net) • Airborne observations of surface-atmosphere fluxes • IMR-PINRO Ecosystem Survey • IMR Barents Sea Winter Survey • Field experiments: Arctic Summer Cloud Ocean Study (ASCOS); Arctic Clouds during Summer Experiment (ACSE); Norwegian Young Sea Ice Cruise 2015 (N-ICE2015); Sea State 2015. • NIVA Barents Sea FerryBox • Global Observing System (GOS; surface synoptic measurements) • Svalbard Automated Weather and Snow Measuring System • PEEX (Pan-Eurasian Experiment)

	Water vapor	• Polish Polar Station Hornsund (WIGOS 01003) • Greenland Ecosystem Monitoring program • Global and Regional GAW • ICOS • Sodankylä supersite (FMI) • PROMICE automatic weather station network • Greenland Climate Network (GC-Net) • Airborne observations of surface-atmosphere fluxes • Field experiments: Arctic Summer Cloud Ocean Study (ASCOS); Arctic Clouds during Summer Experiment (ACSE); Norwegian Young Sea Ice Cruise 2015 (N-ICE2015); Sea State 2015. • Global Observing System (GOS; surface synoptic measurements) • PEEX (Pan-Eurasian Experiment) • Svalbard Automated Weather and Snow Measuring System
	Pressure	• Polish Polar Station Hornsund (WIGOS 01003) • Greenland Ecosystem Monitoring program • Global-GAW • Regional GAW • ICOS • Sodankylä supersite (FMI) • PROMICE automatic weather station network • Greenland Climate Network (GC-Net) • IMR-PINRO Ecosystem Survey • Field experiments: Arctic Summer Cloud Ocean Study (ASCOS); Arctic Clouds during Summer Experiment (ACSE); Norwegian Young Sea Ice Cruise 2015 (N-ICE2015); Sea State 2015. • Global Observing System (GOS; surface synoptic measurements) • PEEX (Pan-Eurasian Experiment)
	Precipitation (amount of liquid precipitation, amount of solid precipitation)	• WMO Integrated Global Observing System (WIGOS) - Regional Basic Synoptic Network (RBSN) - Hornsund 01003 (Polish Polar Station) • Greenland Ecosystem Monitoring program • Global-GAW • Regional GAW • Sodankylä supersite (FMI) • Greenland Climate Network (GC-Net) • Global Observing System (surface synoptic measurements) • PEEX (Pan-Eurasian Experiment)
	Surface radiation budget (surface longwave radiation budget, surface shortwave radiation budget)	• Polish Polar Station Hornsund (WIGOS 01003) • Greenland Ecosystem Monitoring program • Sodankylä supersite (FMI) • PROMICE automatic weather station network • Greenland Climate Network (GC-Net) • Field experiments: Arctic Summer Cloud Ocean Study (ASCOS); Arctic Clouds during Summer Experiment (ACSE); Norwegian Young Sea Ice Cruise 2015 (N-ICE2015); Sea State 2015. • Airborne observations of surface-atmosphere fluxes • Global Observing System (surface synoptic measurements) • PEEX (Pan-Eurasian Experiment)

	Latent and sensible heat fluxes	• Greenland Ecosystem Monitoring program • ICOS • Field experiments: Arctic Summer Cloud Ocean Study (ASCOS); Arctic Clouds during Summer Experiment (ACSE); Norwegian Young Sea Ice Cruise 2015 (N-ICE2015); Sea State 2015. • Sodankylä supersite (FMI) • Airborne observations of surface-atmosphere fluxes
UPPER-AIR	Temperature (tropospheric temperature profile, stratospheric temperature profile, temperature of deep atmospheric layers)	• GRUAN (GCOS Reference Upper Air Network) • Sodankylä supersite (FMI) • IGRA Radiosounding network in the Arctic • Field experiments: Arctic Summer Cloud Ocean Study (ASCOS); Arctic Clouds during Summer Experiment (ACSE); Norwegian Young Sea Ice Cruise 2015 (N-ICE2015); Sea State 2015. • Polarstern Arctic field campaigns
	Wind speed and direction	• GRUAN (GCOS Reference Upper Air Network) • Sodankylä supersite (FMI) • IGRA Radiosounding network in the Arctic • Field experiments: Arctic Summer Cloud Ocean Study (ASCOS); Arctic Clouds during Summer Experiment (ACSE); Norwegian Young Sea Ice Cruise 2015 (N-ICE2015); Sea State 2015. • Polarstern Arctic field campaigns
	Water vapor (Total column water vapour, tropospheric and lower-stratospheric profiles of water vapour, upper tropospheric humidity)	• GRUAN (GCOS Reference Upper Air Network) • Sodankylä supersite (FMI) • IGRA Radiosounding network in the Arctic • Field experiments: Arctic Summer Cloud Ocean Study (ASCOS); Arctic Clouds during Summer Experiment (ACSE); Norwegian Young Sea Ice Cruise 2015 (N-ICE2015); Sea State 2015. Polarstern Arctic field campaigns
	Cloud properties (cloud amount, cloud-top pressure, cloud-top temperature, cloud optical depth, cloud water path (liquid and ice)	• Polish Polar Station Hornsund (WIGOS 01003) • Sodankylä supersite (FMI) • Aerosol, Clouds, and Trace gases Research Infrastructure (ACTRIS) • Arctic Summer Cloud Ocean Study (ASCOS); Arctic Clouds during Summer Experiment (ACSE)

COMPOSITION	Carbon Dioxide, Methane, and other long-lived greenhouse gases (tropospheric CO2 column, tropospheric CO2 profile, tropospheric Carbon	• Greenland Ecosystem Monitoring program • ICOS • Sodankylä supersite • Tower network for atmospheric trace gas mixing-ratio monitoring_NOAA • Tower network for atmospheric trace gas mixing-ratio monitoring_NOAA-PP • Tower network for atmospheric trace gas mixing-ratio monitoring_ENV-CA • Tower network for atmospheric trace gas mixing-ratio monitoring_FMI • Tower network for atmospheric trace gas mixing-ratio monitoring_MPG • Tower network for atmospheric trace gas mixing-ratio monitoring_JR • Tower network for atmospheric trace gas mixing-ratio monitoring_EXE
	Ozone and aerosol, supported by their precursors (Total column ozone, tropospheric ozone, ozone profile in upper and lower stratosphere)	• Global and Regional GAW • Aerosol, Clouds, and Trace gases Research Infrastructure (ACTRIS)

If we are interested in using Arctic observations for atmospheric data assimilation for numerical weather forecasts, one may argue that the Arctic area is small enough that satellite observations together with vertical soundings at a few southern locations is enough to capture the spatial variability. One may also argue that the lack of vertical soundings over most of the polar cap poses a serious constraint to viable Arctic forecasting. The problem is that we don’t know what is limiting forecast quality in the Arctic the most; poor models or lack of observations.

Finally, if we are interested in why the Arctic climate is changing, this opens up yet a new set of questions. To understand this, there is a whole range of processes that we need to understand, most of which are completely absent in Arctic observations. Three things need to be observed better for an understanding of the Arctic weather and climate: 1) The vertical structure of the central Arctic atmosphere; 2) The surface energy budget, and; 3) Properties of Arctic clouds.

1) The Vertical structure encompasses how the thermodynamic and dynamic properties of the atmosphere changes with height. Therefore, it is not really a variable, since it is more than measurement; even more than a local gradient of a measurement. But without soundings of the Arctic atmosphere we are clueless.

2) The surface energy budget is what determines the melting and freezing of sea ice. Over the Arctic Ocean there are no reliable observations of this, except for during brief field campaigns. Most satellite products are unreliable as are models.

3) Some variables are available from satellite in summer; essentially nothing, or very little, is available in winter, at least over the Arctic Ocean. Satellite products are promising but need in-situ ground truth observations, which is lacking in winter.

Many variables need to be measured that currently are not, but observations cannot be viewed in isolation; observations are needed for models but models are also needed for observations.

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 only 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 11. Observing systems classified by the degree of heterogeneity in the uncertainty of their observations from score 6 to 1 (decreasing heterogeneity).

Score	**Observing systems**

6	ICOS FMI AWS GRUAN
5	
4	Radiosounding network in the Arctic
3	ACTRIS
2	FMI snow depth stations NIVA Ferrybox PEEX (Pan-Eurasian EXperiment) Tower network for atmospheric trace gas mixing-ratio monitoring Polish Polar Station Hornsund (WIGOS 01003)
1	AC-AHC2 stable water isotope measurement stations IMR-PINRO Ecosystem Survey IMR Barents Sea Winter Survey Arctic Summer Cloud Ocean Study (ASCOS) in situ field campaign Arctic Clouds during Summer Experiment (ACSE) in situ field campaign Norwegian Young Sea Ice Cruise 2015 (N-ICE2015) Sea State 2015 in situ field campaign Polarstern in situ field campaigns PROMICE Automatic weather stations network Global & regional GAW inside the AMAP geographical boundaries Surface meteorological holdings (GOS) Airborne observations of surface-atmosphere fluxes

The main conclusion based on Table 11 is that most observing systems do not have well defined uncertainty in the majority of their observations. Only very focused networks have been able to set uncertainty requirements for their data, and in some cases, are also able to reach them.

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 12). 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 12. 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 answers are marked in grey (Missing).

Observing system	**Scientific and expert support**	**Funding support**	**Site representativeness (for land-based**
AC-AHC2 stable water isotope measurement stations	1	1	1
IMR-PINRO Ecosystem Survey	1	6	
IMR Barents Sea Winter Survey	1	6	
Arctic Summer Cloud Ocean Study (ASCOS) field campaign	1	1	
Arctic Clouds during Summer Experiment (ACSE) field campaign	1	1	
Norwegian Young Sea Ice Cruise 2015 (N-ICE2015)	1	1	
Sea State 2015 in situ field campaign	1	1	
Polarstern in situ field campaigns	1	1	
Greenland Ecosystem Monitoring Programme	6	6	4
PROMICE Automatic weather station network	6	6	4
Greenland Climate Network	2	3	4
Radiosounding network in the Arctic	3	5	
Global & regional GAW inside the AMAP geographical boundaries	5	5	4
ICOS	5	5	3
ACTRIS	6	6	4
FMI Sodankylä (AWS & snow measurements)	6	6	4
GRUAN	5	6	5
Surface meteorological holdings (GOS)	3	5	1
Tower network for atmospheric trace gas mixing-ratio monitoring	3	3	3
NIVA Barents Sea FerryBox	6	4	
PEEX (Pan-Eurasian EXperiment)	3	5	3
Airborne observations of surface-atmosphere fluxes	4	4	5
Polish Polar Station Hornsund (WIGOS 01003)	4	5	3

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. 37 shows that a majority (11 of 19 classified) of the assessed observation systems are "focused" networks, with 4 each in the categories "broad" and "operational" networks. 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 13 shows the breakdown of the networks according to classification.

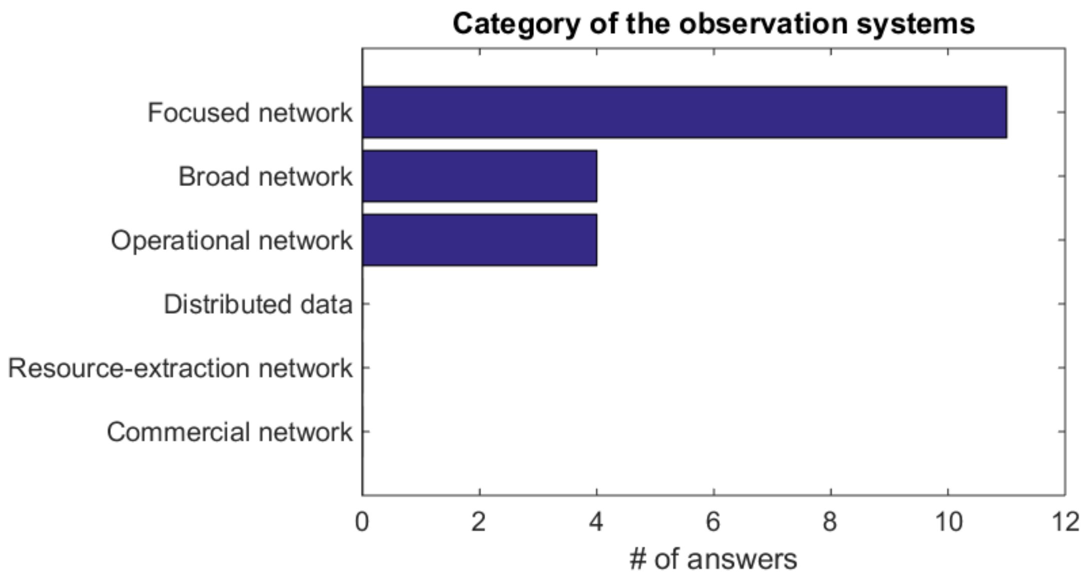


Figure 37. *Categories of the addressed in situ observing systems. The categories are defined according to Eicken et al. (2013).*

Table 13. List of in situ observing systems belonging to each category

Category	In situ observing system
Focused network (confined to specific themes or disciplines)	• ICOS • FMI Sodankylä • Aerosol, Clouds, and Trace gases Research Infrastructure (ACTRIS) • PROMICE automatic weather station network • Greenland Climate Network (GC-Net) • Tower network for atmospheric trace gas mixing-ratio monitoring (NOAA, NOAA-PP, ENV-CA, FMI, MPG, JR, EXE) • Field experiments: Arctic Summer Cloud Ocean Study (ASCOS); Arctic Clouds during Summer Experiment (ACSE); Norwegian Young Sea Ice Cruise (N-ICE2015); Sea State 2015 • Polarstern Arctic field campaigns • NIVA Barents Sea FerryBox • GRUAN (GCOS Reference Upper Air Network) Global Observing System (surface synoptic measurements)
Broad network (it includes a broad range of interdisciplinary observations and projects)	• Polish Polar Station Hornsund (WIGOS 01003) • Greenland Ecosystem Monitoring program • Globaland Regional GAW • PEEX (Pan-Eurasian Experiment)
Operational network (feeding data into weather service and forecasting entities)	• FMI Sodankylä • Radiosounding network in the Arctic • Surface meteorological observations (GOS) • PROMICE automatic weather station network • Tower network for atmospheric trace gas mixing-ratio monitoring_NOAA • NIVA Barents Sea FerryBox

Fig. 38 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 “climate services” and “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. It should also be noted that many of the observing systems were initiated by needs that have nothing or little to do with the atmosphere, but still provide atmospheric relevant data. For example, the IMR surveys in the Barents Sea have a completely different motivation, having to do with practical information for the fishery industry; yet some of the data they produce is relevant for the atmosphere.

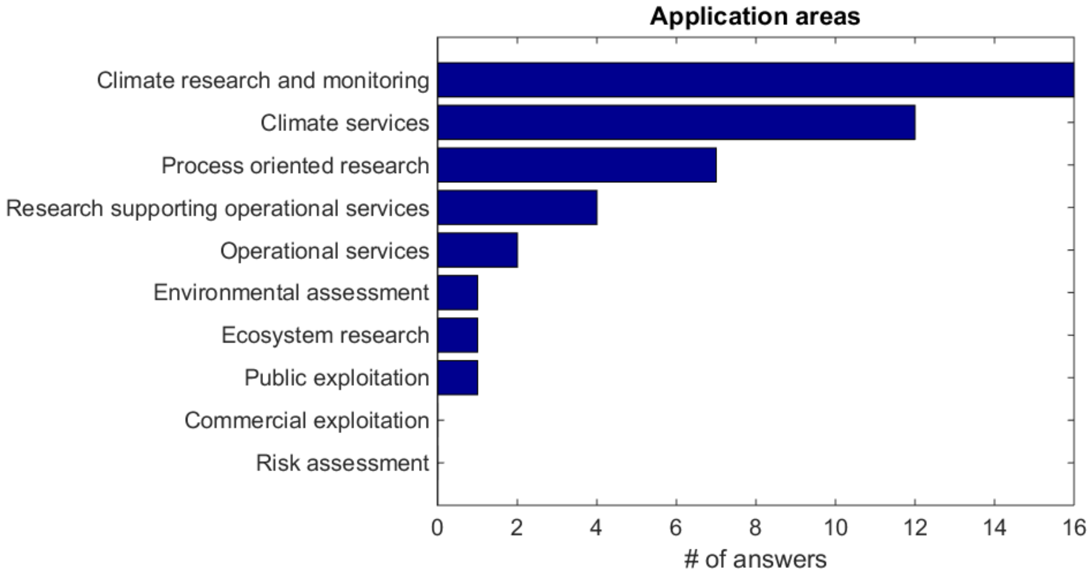


Figure 38. *Application areas of the addressed in situ observing systems.*

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 data records, version control and long term data preservation are assessed for each data collection and classified on a scale from 1 to 6 (Table 14). 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 14. 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**
AC-AHC2 stable water isotope measurement stations	2	2	2	2	2	3
IMR-PINRO Ecosystem Survey	4	3	2	2	1	4
IMR Barents Sea Winter Survey	4	3	2	2	1	4
Arctic Summer Cloud Ocean Study (ASCOS) field campaign	2	3	2	2	2	4
Arctic Clouds during Summer Experiment (ACSE) field campaign	2	3	2	2	2	4
Norwegian Young Sea Ice Cruise 2015 (N-ICE2015)	2	3	2	2	2	4
Sea State 2015 in situ field campaign	2	3	2	2	2	4
Polarstern in situ field campaigns	2	3	2	2	2	4
Greenland Ecosystem Monitoring Programme	2	4	2	3		4
PROMICE Automatic weather station network	5	6	2	6	5	5
Greenland Climate Network	5	4	2	2	2	3
Radiosounding network in the Arctic	6	5	1	6	3	5
Global & regional GAW inside the AMAP geographical boundaries	6	5	2	2	2	5
ICOS	3	5	3	2	2	5
ACTRIS	6	5	5	5	2	5
FMI Sodankylä (AWS & snow measurements)	2	5	2	5	2	4
GRUAN	6	6	5	5	5	5
Surface meteorological holdings (GOS)	6	6	5	4	4	5
Tower network for atmospheric trace gas mixing-ratio monitoring	2 - 4	2	2	3	4	4
NIVA Barents Sea FerryBox	4	3	2	2	2	4
PEEX (Pan-Eurasian EXperiment)	2	2	2	2	2	4
Airborne observations of surface-atmosphere fluxes	2	2	2		2	4
Polish Polar Station Hornsund (WIGOS 01003)	4	3	2	2	2	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.

We focus here on selected data collections (those mentioned in the description of work). 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 D2.6).

4.2.1 General information

The key information on the assessed data collections are summarized in Table 15. 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.

Table 15. Assessed atmospheric data collections

Name of data collection	Variables included in the data collection	Assessor of the data collection	Instruments	Observing System to which the data belong	Administrating Bodies
Data collection “Air temperature, relative humidity, wind direction and speed, precipitation at Russian Arctic stations”	air temperature and relative humidity at 2m, wind speed and direction at 10m, precipitation at 2m	Hanna K. Lappalainen (UHEL); Alexander Mahura (UHEL)	pending (info not available yet)	PEEX (Pan-Eurasian Experiment)	University of Helsinki (UHEL), Institute for Atmospheric and Earth System Research (INAR), & owners of the measurement stations
PROMICE AWS data	2m-air temperature 2m-wind speed and direction 2m air pressure Incoming and outgoing shortwave radiation incoming and outgoing longwave radiation relative humidity	GEUS	Temperature: Rotronic in aspirated Rotronic assembly Model: MP100H-4-1-03-00-10DIN Wind: R.M. Young, model: 05103-5 Pressure: Barometer Setra CS100-Setra, model 278 Shortwave radiation: Kipp & Zonen CNR1 Longwave radiation: Kipp & Zonen CNR4 Relative humidity: Rotronic aspirated hygro-/thermometer hygroClip S3 in Rotronic assembly	PROMICE AWS network	GEUS
IGRA (Soundings from Canada, United States, Greenland, Faroe Islands, Norway, and Finland)	Pressure, Geopotential height, Temperature, Potential temperature, Vapor pressure, Saturation vapor pressure, Relative humidity, Zonal wind, Meridional wind	Tuomas Naakka (FMI)	Vaisala RS92 Vaisala RS41 Lockheed Martin LMS-6 Sippican LMS6 Modem GPSonde M10 BAT-4G	Radiosounding network in the Arctic	National Oceanic Atmospheric Administration (NOAA)/National Center Environmental Information (NCEI)
IGRA (Soundings from Russia)	Pressure, Geopotential height, Temperature, Potential temperature, Vapor pressure, Saturation vapor pressure, Relative humidity, Zonal wind, Meridional wind	Tuomas Naakka (FMI)	AVK-MRZ AVK-AK2-02 MARL-A / VEKTOR-M -AK2-02 AVK-I-2012 AVK-BAR MARL-A / VEKTOR-M -I-2012 MARL-A / VEKTOR-M -MRZ-3MK	Radiosounding network in the Arctic	National Oceanic Atmospheric Administration (NOAA)/National Center Environmental Information (NCEI)

			MARL-A / VEKTOR-M -BAR		
Arctic Summer Cloud Ocean Study (ASCOS) - in situ field campaign (central Arctic Ocean sea ice)	Tropospheric temperature; Tropospheric relative humidity; Tropospheric wind speed; Tropospheric wind direction; Surface net longwave radiation; Surface net shortwave radiation; Surface sensible heat, latent heat, and momentum fluxes Cloud mask; Cloud liquid water path; Cloud ice water content profile	Joseph Sedlar (MISU)	Radiosonde temperature, humidity, pressure and wind: Vaisala RS92 PTU; Vaisala RS92 GPS receiver; Longwave radiation: Eppley PIR; Shortwave radiation Eppley PSP; Turbulent fluxes: Campbell CSAT3/Metek uSonic and Licor LI-7500; Clouds: Ka-band cloud radar; Vaisala CL51 ceilometer; Radiometrics dual channel microwave radiometer combined with Vaisala RS92 sondes;	ASCOS in situ field campaign; central sea ice observatory	Department of Meteorology, Stockholm University (MISU)
Arctic Clouds during Summer Experiment (ACSE) - in situ field campaign (Arctic Ocean transect)	Tropospheric temperature; Tropospheric relative humidity; Tropospheric wind speed; Tropospheric wind direction; Surface downwelling longwave and shortwave radiation; Surface sensible heat, latent heat, and momentum fluxes; Cloud mask; Cloud liquid water path; Cloud ice water content profile	Joseph Sedlar (MISU)	Radiosonde temperature, humidity, pressure and wind: Vaisala RS92 PTU; Vaisala RS92 GPS receiver; Longwave radiation: Eppley PIR; Shortwave radiation Eppley PSP; Turbulent fluxes: Metek uSonic and Licor LI-7500; Clouds: W-band cloud radar; Vaisala CL51 ceilometer; Radiometrics dual channel microwave radiometer combined with Vaisala RS92 sondes;	ACSE in situ field campaign; central observatory onboard Icebreaker Oden for Arctic transect	Department of Meteorology, Stockholm University (MISU)
Norwegian Young Sea Ice Cruise (N-ICE2015) - in situ field campaign (central Arctic Ocean sea ice)	Tropospheric temperature, relative humidity and wind Speed and direction; Surface net longwave radiation; Surface net shortwave radiation; Surface sensible heat, latent heat, and momentum fluxes	Joseph Sedlar (MISU)	Soundings: Vaisala RS92 PTU; Vaisala RS92 GPS receiver; Radiation: Kipp & Zonen CGR4; Kipp & Zonen CMP22; Turbulent fluxes: Campbell CSAT3; Campbell EC155;	N-ICE2015 in situ field campaign; central sea ice observatory	Norwegian Polar Institute (NPI)

Sea State 2015 - in situ field campaign (central Arctic Ocean sea ice)	Tropospheric temperature; Tropospheric relative humidity; Tropospheric wind speed; Tropospheric wind direction; Surface downwelling longwave and shortwave radiation; Surface sensible heat, latent heat, and momentum fluxes	Joseph Sedlar (MISU)	Soundings: Vaisala RS92 PTU & Vaisala RS92 GPS receiver; Radiation: Eppley PIR; Eppley PSP; Metek uSonic-3 - Licor 7500	Sea State 2015 in situ field campaign onboard Icebreaker Sikuliaq	Office of Naval Research
Polarstern - in situ field campaigns (central Arctic Ocean sea ice)	Tropospheric temperature; Tropospheric relative humidity; Tropospheric wind speed; Tropospheric wind direction	Joseph Sedlar (MISU)	Vaisala RS92 PTU; Vaisala RS92 PTU; Vaisala RS92 GPS receiver; Vaisala RS92 GPS receiver	Polarstern in situ field campaigns; summer Arctic Ocean cruises onboard Polarstern	Alfred Wegener Institute, Helmholtz Center for Polar and Marine Research
AIRMETH_vertical_profiles_Polar5	Concentration of CH4, CO2 and water vapour, pressure, air temperature	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.), PT100, Vaisala HMT-330	Airborne observations of surface-atmosphere fluxes	GFZ
AIRMETH_vertical_profiles_Helipod	Concentration of CH4, CO2 and water vapour, pressure, air temperature	Katrin Kohnert, Andrei Serafimovich, Torsten Sachs (GFZ)	Helicopter-towed system Helipod (Technische Universität Braunschweig) equipped with open path CO2/H2O gas analyzer LI-7500 (Licor), open path CH4 analyzer LI-7700 (Licor, only in 2014), 5-hole probe	Airborne observations of surface-atmosphere fluxes	GFZ
FMI Sodankylä AWS	Air temperature, precipitation (among others)	Anna Kontu (FMI)	PT100, Vaisala VRG	FMI Sodankylä	FMI
FMI Sodankylä Snow depth station	Air temperature	Anna Kontu (FMI)	PT100	FMI Sodankylä	FMI
GRUAN	Temperature, humidity, winds	Peter Thorne (NUIM)	Radiosonde (Vaisala RS92, soon to include RS41)	GRUAN	GCOS

Surface meteorological holdings	Temperature, humidity, pressure, precipitation, windspeed + direction, snowfall/depth	Peter Thorne (NUIM)	Standard meteorological sensors	GOS	WMO
Polish Polar Station Hornsund (WIGOS 01003)	Air temperature, humidity, wind speed, wind direction, atmospheric pressure, dew point, solar radiation	Tomasz Wawrzyniak (IGPAN)	Sensors: HMP155, PTB330, WMT702, CMP11 Precipitation rain gauges: Hellman (6h interval since 1978),	Polish Polar Station Hornsund (WIGOS 01003)	Institute of Geophysics, Polish Academy of Sciences
NIVA Barents Sea FerryBox	Wind speed and direction, Surface radiation budget	Andrew King, Kai Sørensen, Pierre Jaccard (NIVA)	Gill WindObserver II, Trios RAMSES	NIVA FerryBox	Norwegian Institute for Water Research (NIVA)
AC-AHC2 stable water isotope measurement stations	HDO, H218O, H216O in vapour	Harald Sodemann (UiB)	Picarro CRDS analyzer (different models) Lost Gatos CRDS analyzer (different models)	AC-AHC2 bottom-up network of stations	CNRS-LSCE, AWI, UiB
GAW Aerosol programme	Aerosol scattering coefficient, aerosol absorption coefficient, aerosol number, aerosol size distribution	Eija Asmi (FMI)	Nephelometer, Aethalometer/MAAP/CLAP/PSAP, Condensation particle counter, SMPS/DMPS	GAW Aerosols	Finnish Met Institute, Univ Helsinki, Stockholm Univ, NOAA, Env Canada, Institute of Nuclear and Radiological Science & Technology
IMR-PINRO Ecosystem Survey Wind measurements	Wind strength and direction	Geir Ottersen (IMR)	Missing	IMR-PINRO Ecosystem Survey	IMR and PINRO
IMR Barents Sea Winter Survey Wind measurements	Wind strength and direction	Geir Ottersen (IMR)	Missing	IMR Barents Sea Winter Survey	IMR
ACTRIS cloud properties	Cloud liquid water path Vertical profiles of: Cloud target classification, Cloud fraction, Cloud liquid water content, Cloud ice water content.	Ewan O'Connor (FMI)	Cloud radar, Ceilometer, multi-wavelength microwave radiometer.	ACTRIS	ACTRIS
Arctic upgraded aerosol absorption coefficient	Aerosol absorption coefficient	John Backman, Lauren Schmeisser, Eija Asmi	Aethalometer	GAW/IASOA/ACTRIS	GAW/IASOA/ACTRIS

Ceilometer products upgraded	Hydrometeor classification	Ewan O’Connor	Ceilometer	IASOA/ACTRIS	IASOA/ACTRIS

Technology maturity readiness of the instruments used to generate the measured parameters of the assessed data collections (in Table 15) is provided in Table 16. 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 16. 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**
PROMICE AWS data	Rotronic in Rotronic assembly (aspirated), Model: MP100H-4-1-03-00-10DIN	Air temperature 2m
	R.M. Young, model: 05103-5	Wind speed 2m Wind direction 2m
	Rotronic Hygro-/thermometer HygroClip S3, aspirated, in Rotronic assembly	Relative humidity 2m
	Setra Barometer CS100-Setra model 278	Air pressure 2m
	Kipp & Zonen CNR4	Longwave radiation near-surface
	Kipp & Zonen CNR1	Shortwave radiation near-surface
Integrated Global Radiosonde Archive (IGRA) (Soundings from Canada, United States, Greenland, Faroe Islands, Norway, and Finland)	Vaisala RS92	Atmospheric temperature, relative humidity, wind speed and wind direction
	Vaisala RS41	Atmospheric temperature, relative humidity, wind speed and wind direction
	Lockheed Martin LMS-6	Atmospheric temperature, relative humidity, wind speed and wind direction
	Sippican LMS6	Atmospheric temperature, relative humidity, wind speed and wind direction
	Modem GPSonde M10	Atmospheric temperature, relative humidity, wind speed and wind direction
	BAT-4G	Atmospheric temperature, relative humidity, wind speed and wind direction

Integrated Global Radiosonde Archive (IGRA) (Soundings from Russia)	AVK-MRZ	Atmospheric temperature, relative humidity, wind speed and wind direction
	AVK-AK2-02	Atmospheric temperature, relative humidity, wind speed and wind direction
	MARL-A / VEKTOR-M -AK2-02	Atmospheric temperature, relative humidity, wind speed and wind direction
	AVK-I-2012	Atmospheric temperature, relative humidity, wind speed and wind direction
	AVK-BAR	Atmospheric temperature, relative humidity, wind speed and wind direction
	MARL-A / VEKTOR-M -I-2012	Atmospheric temperature, relative humidity, wind speed and wind direction
	MARL-A / VEKTOR-M -MRZ-3MK	Atmospheric temperature, relative humidity, wind speed and wind direction
	MARL-A / VEKTOR-M -BAR	Atmospheric temperature, relative humidity, wind speed and wind direction
Data collection “Air temperature, relative humidity, wind direction and speed, precipitation at Russian Arctic stations”	Various instruments (note exactly the same at all 11 stations) for air temperature, humidity, wind characteristics, and precipitation measurements. TRL-2	air temperature, relative humidity, and precipitation at 2 m, wind speed and direction at 10 m
In situ field campaign atmospheric thermodynamics and winds (ASCOS, ACSE, N-ICE2015, Sea State 2015, Polarstern)	Vaisala RS92	Atmospheric temperature, relative humidity, wind speed and wind direction
In situ field campaign surface radiation (ASCOS, ACSE, N-ICE2015, Sea State 2015)	Eppley PIR	Longwave radiation
	Eppley PSP	Shortwave radiation
	Kipp & Zonen CGR4	Longwave radiation
	Kipp & Zonen CMP22	Shortwave radiation
In situ field campaign surface sonic anemometers, open/closed path gas analyzers (ASCOS, ACSE, N-ICE2015)	Campbell CSAT3	High frequency 3D wind field – Sensible heat, Latent, and Momentum heat fluxes
	Metek uSonic	High frequency 3D wind field – Sensible heat, Latent, and Momentum heat fluxes
	Licor LI-7500	High frequency moisture content - Latent heat flux
	Campbell EC155	High frequency moisture content - Latent heat flux
In situ field campaign cloud properties (ASCOS, ACSE)	NOAA Ka-band cloud radar NOAA W-band cloud radar Vaisala CL51 ceilometer	Cloud mask Cloud boundaries
	Radiometrics dual channel microwave radiometer	Cloud liquid water path
	NOAA Ka-band cloud radar NOAA W-band cloud radar Vaisala CL51 ceilometer	Cloud ice water content profiles

	Radiometrics dual channel microwave radiometer Vaisala RS92	
AIRMETH_vertical_profiles_Polar5	Los Gatos Research FGGA-24EP (RMT-200 in 2012) Open wire Pt100 in an unheated Rosemount housing	CH4, CO2, and water vapor concentration, air pressure and temperature
AIRMETH_vertical_profiles_Helipod	Open path CH_4 sensor Li 7700 (Licor) Open path CO_2 and H_2O sensor Li 7500 (Licor) Open wire Pt100 (Rosemount) Fine wire (Dantec) Lyman Alpha sensor L6 (Buck Research)	CH4, CO2, and water vapor concentration, air pressure and temperature
FMI Sodankylä AWS	PT100 Vaisala VRG	Air temperature Precipitation
FMI Sodankylä Snow depth station	PT100	Air temperature
GRUAN	Vaisala RS92 (TRL9)	PTU
Surface meteorological holdings	Various (TRL9)	Temperature, humidity, pressure wind speed and direction, precipitation, snowfall / snowcover
NIVA Barents Sea FerryBox	Gill Wind Observer	Wind speed and direction
NIVA Barents Sea FerryBox	Trios RAMSES	Hyperspectral radiance/irradiance
AC-AHC2 stable water isotope measurement stations	Picarro CRDS analyzers, series L11xx-i, L21xx-I Los Gatos CRDS analyzers WVIA	Stable isotopes HDO, H218O, H216 in water vapour
GAW Aerosols	Nephelometer, Aethalometer/MAAP/CLAP/PSAP, Condensation particle counter, SMPS/DMPS (TRL4)	Aerosol scattering and absorption coefficient, aerosol number, aerosol size distribution
IMR-PINRO Ecosystem Survey Wind measurements	TRL1-2	Atmospheric wind speed and direction (surface level)
IMR Barents Sea Winter Survey Wind measurements	TRL1-2	Atmospheric wind speed and direction (surface level)
ACTRIS cloud properties	Metek or RadiometerPhysics cloud radar, Vaisala Ceilometer, RadiometerPhysics multi-channel microwave radiometer (TRL9)	Profile: Cloud target classification, cloud fraction, cloud liquid and ice water content. Column: cloud liquid water path
Arctic aerosol absorption coefficient	Aethalometer (TRL3)	Absorption coefficient
Arctic upgraded aerosol absorption coefficient	MAAP, PSAP, CLAP (TRL4)	Absorption coefficient
Ceilometer products upgraded	Ceilometer (TRL9)	Hydrometeor classification

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 17, spatial vertical and horizontal coverage (i.e. measurement locations) of each data collection is compared with the corresponding requirements. In Table 18, spatial vertical and horizontal resolution (i.e. density of measurements) of each data collection is compared with the corresponding requirements. In Tables 19 and 20 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 21 presents the data collections timeliness (i.e. how fast the data become available after collection).

Table 17. Spatial coverage

Data collection	Horizontal coverage of observations	Vertical coverage of observations	Required horizontal coverage	Required vertical coverage	Comparison: observed vs required
Data collection "Air temperature, relative humidity, wind direction and speed, precipitation at Russian Arctic stations"	measurements are performed at exact geographical points/ locations of the sites (at single locations)	at 2 (air temperature, relative humidity, precipitation) and at 10 m (wind speed and direction) height above the ground	Russian-Arctic (over land)	Single level	more dense network of stations would be desirable along the longitudinal belt of the Russian Arctic; although vertical coverage is following the standard measurements, more measurements at different levels/heights within the surface layer of the atmosphere (i.e. first 100 m) would be desirable.
PROMICE AWS data (air temp 2m, rel.hum., air pressure 2m, wind speed/direction, SW and LW radiation budget)	Parameters are measured on 20+ automatic weather stations placed in transects (2-3 AWS in each) on the Greenland ice sheet in the ablation area, ie. point measurements	Measurements are made at ca. 2 m level (ranging from 0-2.7m in reality due to varying snow amounts)	Regionally representative capturing climatological conditions relevant for regional climate models	It would be desirable to resolve the boundary-layer with more than a single level	Horizontal: Ideally an additional transect should be operated between Tasiilaq in SE Greenland and Qassimiut in S Greenland to capture meteorological conditions in this important region. Other transects that should be considered would be in the central Melville Bay (Kullorsuaq) and at Petermann/Humboldt glaciers in N Greenland. Vertical: The boundary-layer would be better characterized by measurement of some parameters, like air temp, wind speed/dir and RH at more than one level. Realistically, only 1.5 and 2.5 m are feasible due to limitations on station size.
Integrated Global Radiosonde Archive (IGRA) (Soundings from Canada, United States, Greenland, Faroe Islands, Norway, and Finland)	All permanent sounding stations in the Arctic between longitudes 170°E and 30°E	approx. 65% of soundings reach the 10 hPa level and 90% soundings reach the 30 hPa level in 2017 (based on the highest pressure level archived in IGRA)	The whole Arctic in Sector from Europe to North America.	surface - 10 hPa (goal) surface - 30 hPa (threshold)	Sounding network covers most of land area so that the distance between stations not exceed 1000 km, but any permanent radiosounding station is not situated in the central Arctic Ocean. Most of soundings achieve the threshold vertical coverage.

Integrated Global Radiosonde Archive (IGRA) (Soundings from Russia)	All permanent sounding stations in the Arctic between longitudes 30°E and 170°E (in Russia)	approx. 65% of soundings reach the 10 hPa level and 90% soundings reach the 30 hPa level in 2017 (based on the highest pressure level in IGRA)	The whole Arctic in Russian sector	surface - 10 hPa (goal) surface - 30 hPa (threshold)	Sounding network covers most of land area so that the distance between stations not exceed 1000 km, but any permanent radiosounding station is not situated in the central Arctic Ocean. More than half of soundings achieve the threshold vertical coverage.
In situ field campaign atmospheric thermodynamics, atmospheric winds, surface energy budget, and cloud properties (ASCOS, ACSE, N-ICE2015, Sea State 2015, Polarstern)	Central observatory point measurements within the central Arctic Ocean; campaigns based either onboard icebreakers, or from a central observatory on sea ice. Horizontal coverage generally limited to nadir or hemispheric for surface radiation.	Profile measurements, integrated column values, or near-surface measurements.	Area covered by the cruises.	Surface measurements do not need vertical coverage. Profiles of thermodynamics should cover the full troposphere and lower stratosphere	Where in situ profiles are made, the vertical coverage typically extends across the full troposphere and lower stratosphere. In situ campaigns that involve transects (ACSE, Polarstern) increase the spatial coverage of the observations, but these are still limited specific locations or cruise tracks. Campaigns that involve a central observing facility based either on the icebreaker or on an ice floe collect measurements that are typically valid only at the point location. Therefore, the required spatial coverage will never be met by in situ field campaigns.
AIRMETH vertical profiles Polar5	AIRMETH vertical profiles MackenzieCAN AIRMETH vertical profiles NorthSlopeAK	Profile	One study area in each mayor arctic zone (Alaska, Canada, Russia, Europe)	Profile	Horizontal coverage: lacking reliable data for Europe (Russia covered by AIRMETH vertical profiles Helipod) Vertical coverage requirement is met already
AIRMETH vertical profiles Helipod	AIRMETH vertical profiles LenaDelta	Profile	Obs. from each mayor Arctic zone (Alaska, Canada, Russia, Europe)	Profile	Lacking reliable data for Europe (Canada and Alaska covered by AIRMETH vertical profiles Polar5) Vertical coverage requirement is met already
FMI Sodankylä AWS	Point measurement 67.3N, 26.6E	Single level	Point	Single level	Network covers whole Finland

FMI Sodankylä Snow depth stations	Point measurements Open/Forest (N67.3 E26.6),(N67.3 E26.6) Peatland (N67.3E26.6)	Single level	Point measurements	Single level	Stations in the most important land cover types close to other instruments.
GRUAN	3 stations (Barrow, Ny Alesund, Sodankyla)	2-second resolution from ascent to burst point	N/A	Full profile to 10hPa	Met depending upon synoptic conditions and balloon integrity effects of burst point (higher than most standard sites)
WIGOS - 01003 - Polish Polar Station Hornsund	measurements are performed at exact geographical point/ locations of the site (at single location)	at 2m (air temperature, relative humidity, precipitation) and at 10 m (wind speed and direction) height above the ground	more dense network of stations would be desirable in Southern Spitsbergen	Single level	more dense network of stations would be desirable
Surface meteorological holdings	3000 stations over land	Single level measurement	Pan-Arctic (over land)	Single level	Not met to threshold. The density of the station is too low in some areas to capture the spatial variability.
NIVA Barents Sea FerryBox wind speed/direction and hyperspectral radiance/irradiance	NIVA_FerryBox, multi points: (69.6,18.9),(70.5,20.7),(74.4,18.4),(78.0,12.9),(78.1,13.9)	5 m for wind and 0 m for radiance/irradiance	N/A	N/A	N/A
Atmospheric Trace Gas Mixing Ratios	pan-Arctic tower network	multiple sensor heights, varying by tower	pan-Arctic	N/A	a quantitative assessment of network coverage is the core objective for partner MPG within INTAROS WP2
AC-AHC2 stable water isotope measurement stations	several stations in the European Arctic including Greenland and sub-Arctic	intake at some distance from surface, sometimes several levels	pan-Arctic	vertical profiles of the lower troposphere	in the European Arctic, stations have gap in eastern Scandinavia. Aircraft campaigns needed to profile vertically to complement surface measurements.
GAW Aerosols	Each variable measured at 4-6 stations in the Arctic	single level, surface	sufficient to determine "temporal distribution of aerosol properties related to climate forcing and air quality on	single level, surface	considering the short life-time of aerosols and the vast heterogenic area of the Arctic, 4-6 measurement locations is hardly representative to give a comprehensive picture of aerosols variability in the Arctic (same conclusion than in e.g. Schmeisser et al., 2018)

			regional, hemispheric and global spatial scale”		Not sufficient
ACTRIS cloud properties	point locations: 3 stations measuring continuously	profile	regionally representative	profile	Vertical profile sufficient Spatial representative not sufficient for much of the Arctic
IMR-PINRO Ecosystem Survey Wind measurements	Measured at hydrographic stations in Barents Sea	Single level (ship height)	more dense network of stations desirable	N/A	Sufficient for hydrography and ecosystem purposes, not for atmospheric studies
IMR Barents Sea Winter Survey Wind measurements	Measured at hydrographic stations in Barents Sea	Single level (ship height)	more dense network of stations desirable	N/A	Sufficient for hydrography and ecosystem purposes, not for atmospheric studies
Aerosol absorption coefficient upgraded	6 Arctic stations	single level, surface	spatio-temporal distribution of aerosol properties related to climate forcing and air quality on multi-decadal time scales and on regional, hemispheric and global spatial scale	single level, surface	Not sufficient to meet the requirements (see: Schmeisser, L., et al. https://doi.org/10.5194/acp-2017-1117, in review, 2018)
Hydrometeor classification upgraded	8 Arctic stations	0-7.7 km (some 0-15 km) but vertical profile suffers attenuation by cloud and precipitation	spatio-temporal distribution of cloud and hydrometeor properties to enable NWP/climate model evaluation at regional/global scales	Full vertical profile of troposphere (about 0-10 km in Arctic)	Not yet sufficient to meet requirements.

Table 18. Spatial resolution

Data collection	Horizontal resolution of observations	Vertical resolution of observations	Required horizontal resolution	Required vertical resolution	Comparison: observed vs required
PROMICE AWS data (air temp 2m, rel.hum., air pressure 2m, wind speed/direction, SW and LW radiation budget)	Measured at geographical points	Measured at a single level	Locally representative	Several levels in the boundary-layer	Horizontal: It would be desirable to carry out dedicated campaigns to quantify the degree of representativeness of individual parameters Vertical: it would be an improvement with measurement of selected variables at 2-3 levels
Data collection "Air temperature, relative humidity, wind direction and speed, precipitation at Russian Arctic stations"	measurements are performed at exact geographical points/ locations of the sites (at single locations)	Single level	Locally representative	N/A	although vertical coverage is following the standard measurements, but more measurements at different levels/heights within the surface layer of the atmosphere (i.e. first 100 m) would be desirable. The spatial representativeness of the stations is unknown
Integrated Global Radiosonde Archive (IGRA) (Soundings from Canada, United States, Greenland, Faroe Islands, Norway, and Finland)	Distance between closest sounding stations varies approx. 300 km to approx. 1000 km.	approx. 10 m	1000 km	0.3 km (goal) 1 km (breakthrough) 3 km (threshold)	Most of land areas the distance between stations fulfill the requirement that the distance between sounding stations should not exceed 1000 km. The areas, where the requirement of maximum distance between sounding station is not satisfied are considered as spatial gab in the network. Soundings provide better vertical resolution than requirements.
Integrated Global Radiosonde Archive (IGRA) (Russia)	Distance between closest sounding stations varies approx. 200 km to approx. 1000 km	finer than 0.3 km	1000 km	0.3 km (goal) 1 km (breakthrough) 3 km (threshold)	Most of land areas the distance between stations fulfill the requirement that the distance between sounding stations should not exceed 1000 km. The areas, where the requirement of maximum distance between sounding station is not satisfied are considered as spatial gab in the network. Soundings provide better vertical resolution than requirements.

In situ field campaign atmospheric thermodynamics and atmospheric winds	Point measurements, lacking a spatial component	Thermodynamic sounding profiles are generally interpolated to 10-30 m vertical resolution	15 km 100 km 500 km	0.3 km 1 km 3 km	Horizontal resolution requirements will never be met for in situ field campaign profiling Vertical resolution is generally much better than the goal requirement
In situ field campaign surface radiative fluxes	Point measurements, lacking a spatial component.	Surface fluxes have no vertical information.	5 km 15 km 50 km	N/A	Although surface radiation measurements are measured at a single point, they are generally representative of the full viewing hemisphere, adding to the spatial coverage
In situ field campaign surface turbulent fluxes	Point measurements, lacking a spatial component.	Surface turbulent fluxes have no vertical information.	N/A	N/A	
Cloud mask / cloud fraction	Point measurements, lacking a spatial component	30 - 100 m	0.5 km 2 km 10 km		From a zenith-viewing remote sensing perspective, there is no direct horizontal information on cloud mask/fraction
Cloud liquid water path	Point measurements, lacking a spatial component	Vertically integrated quantity; no vertical information	0.5 km 2 km 10 km	N/A	Point measurement; in situ field campaign observations of liquid water path will never meet the horizontal resolution requirements
Cloud ice water content profiles	Point measurements, lacking a spatial component	30 - 100 m	0.5 km 2 km 10 km	0.1 km 0.17 km 0.5 km	Point measurement; in situ field campaign observations of ice water content will never meet the horizontal resolution requirement. The vertical resolution requirements are met at the goal level.
AIRMETH vertical profiles Polar5	Moving platform	N/A	N/A	N/A	The spatial resolution depends on the speed of the aircraft. Measurements taken at 100 Hz. Averaging distance of fluxes depends on the atmospheric stability. Vertical resolution is not applicable to horizontal flights.
AIRMETH vertical profiles Helipod	Moving platform				As above
FMI Sodankylä AWS	Point measurement	Single level	N/A	N/A	Network covers whole Finland.
FMI Sodankylä Snow depth stations	Point measurements	Single level	N/A	N/A	Stations in the most important land cover types close to other instruments.
GRUAN	Point and drift	2-second	N/A	Full profile	Met

Polish Polar Station Hornsund (WIGOS 01003)	Point measurement	Single level	Locally representative	N/A	more measurements at different levels/heights would be desirable. The spatial representativeness of the station is unknown.
Surface meteorological holdings	Kms to 1000s of kms	Single level	WMO RRR (variable dependent)	N/A	Not met to threshold / breakthrough
NIVA Barents Sea FerryBox wind speed/direction and hyperspectral radiance/irradiance	approx. 30-45 m	1) Single level measurement			
Atmospheric Trace Gas Mixing Ratios	Point measurement	Discrete measurements at multiple lev.	N/A	N/A	-
AC-AHC2 stable water isotope measurement stations	1000s of kms	surface supplemented by profiles	500 km 1500 km 3000 km	lower-troposphere profiles at 10s of m	sites need to be located in accordance with weather system/storm track characteristics and near sea-ice edge
GAW Aerosols	Point measurements (4-6 points in tot.)	surface, one level, 2-10 m above surface	at least 1000km	surface, one level, 2-10 m above surface	Network is too sparse to cover all Arctic, especially lack of observations in central parts
Actris cloud properties	Point measurements (3 points in total)	30 -50 m resolution throughout troposphere	at least 1000 km	250 m	Network is too sparse to cover all Arctic, vertical resolution is sufficient
IMR-PINRO Ecosystem Survey Wind measurements	Obs. at hydrographic stations in Barents Sea	Single level (ship height)	denser network of stations desirable	N/A	Sufficient for hydrography and ecosystem purposes, not for atmospheric studies
IMR Barents Sea Winter Survey Wind measurements	Obs. at hydrographic stations in Barents Sea	Single level (ship height)	denser network of stations desirable	N/A	Sufficient for hydrography and ecosystem purposes, not for atmospheric studies
Aerosol absorption coefficient upgraded	Point measurements (6 points in total)	surface, one level, 2-10 m above surface	at least 1000 km	surface, one level, 2-10 m above surface	Network is too sparse to cover all Arctic, especially lack of observations in central parts

Hydrometeor classification upgraded	Point location (8 vertical columns)	10-30 m	< 1000 km (< 100 km close to ice edge or coastline)	100 m	Network is too sparse to cover Arctic. Vertical profile resolution more than adequate, but full profile not always captured as profile suffers from attenuation by intervening cloud and precipitation

Table 19. Temporal coverage

Data collection	**Temporal coverage of observations**	**Required temporal coverage**	**Comparison: observed vs required**
PROMICE AWS data (air temp 2m, rel.hum., air pressure 2m, wind speed/direction, SW and LW radiation budget)	Network initiated 2008-2010 and ongoing.	>30 years and onwards	Climatological applications require longterm monitoring. The dataset will eventually reach >30 years and should be continued to monitor climate change over time
Data collection “Air temperature, relative humidity, wind direction and speed, precipitation at Russian Arctic stations”	earliest start of time-series (among 11 stations) is from 1930 at Igarka GeoCryLab	continuation of observations is needed	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)
Integrated Global Radiosonde Archive (IGRA) (Soundings from Canada, United States, Greenland, Faroe Islands, Norway, and Finland)	IGRA contains almost all available sounding data from permanent sounding stations	Continuous observation	The requirement of continuous observation is not fulfilled for every stations.
Integrated Global Radiosonde Archive (IGRA) (Russia)	IGRA contains almost all available sounding data from permanent sounding stations	Continuous observation	The requirement of continuous observation is not fulfilled for every stations.
ASCOS in situ field campaign	August - September 2008	Continuous observation	Requirement of continuous observation will not be fulfilled by in situ field campaigns
ACSE in situ field campaign	July - October 2011	Continuous observation	Requirement of continuous observation will not be fulfilled by in situ field campaigns
N-ICE2015 in situ field campaign	January - June 2015	Continuous observation	Requirement of continuous observation will not be fulfilled by in situ field campaigns
Sea State 2015 in situ field campaign	October - November 2015	Continuous observation	Requirement of continuous observation will not be fulfilled by in situ field campaigns

Polarstern in situ field campaigns	June to October for years: 2007, 2008, 2009, 2010, 2011, 2012, 2014	Continuous observation	Requirement of continuous observation will not be fulfilled by in situ field campaigns
AIRMETH_vertical_profiles_Polar5	2012.06 – 2012.07 2013.07 2016.08 – 2016.09	Biannual	On average the requirements are almost met and campaigns should be continued in the future.
AIRMETH_vertical_profiles_Helipod	2012.08.09 – 2012.08.15 2014.04.06 – 2014.08.22	Biannual	The requirements are not yet met and campaigns should be continued in the future.
FMI Sodankylä AWS	start: 2006.10.24	Continuous	Before 2006 manual observations for over 100 years.
FMI Sodankylä Snow depth stations	start: 2006.11.17	Continuous	Continuous measurements.
GRUAN	2006 to present	2006 on	met
Polish Polar Station Hornsund (WIGOS 01003)	1978 - ongoing	Continuous observation	Continuation and development of instruments and locations
Surface meteorological holdings	1807 to present (although most start much more recently and several do not continue through present)	Continuous observations	Impossible to assess
NIVA Barents Sea FerryBox wind speed/direction and hyperspectral radiance/irradiance	29 roundtrips between Tromsø and Longyearbyen in 2017. Each voyage takes 5-6 days with breaks in between each voyage. An example of trips: 2017.10.17 to 2017.10.23 2017.10.27 to 2017.11.02	Continuous during the cruises	
Atmospheric Trace Gas Mixing Ratios	Earliest data start 1971. Part of the data is continuous	continuous	The temporal coverage of the currently existing systems is adequate for the past, but operation should be continued into the future
AC-AHC2 stable water isotope measurement stations	stations starting at different years since 2011	continuous	Since the network is organized bottom-up through different national projects, start and end dates of measurements are variable
GAW Aerosols	Number: Earliest since 1990 Absorption: Earliest since 1997 Scattering: Earliest since 2004 Size distribution: Earliest since 1997	continuous	The established data series have been continued to date - however, even the longest data series are only <30 years and most of the observations (about 75%) have been started after year 2000.
ACTRIS cloud properties	Since 2016	continuous	Continuous monitoring required for NWP and climate applications

IMR-PINRO Ecosystem Survey **Wind measurements**	Annually in August-September 2004-ongoing	More frequently	Ideally time series had started earlier (but possible to combine with measurements from earlier cruises)
IMR Barents Sea Winter Survey **Wind measurements**	Annually in January-February 1976-	More frequently	
Aerosol absorption coefficient upgraded	2012-2014	long-term	3 years not enough for trend studies, however, sufficient for seasonal variability analysis
Hydrometeor classification upgraded	2013-present, some stations since 2000	long-term	Sufficient for model evaluation, and seasonal/diurnal analyses; not yet for trend analyses

Table 20. Temporal resolution

Data collection	**Temporal resolution of observations**	**Required temporal resolution**	**Comparison: observed vs required**
PROMICE AWS data (2m air temp, rel.hum., air pressure, wind speed/ direction, SW and LW radiation budget)	10 minutes	10 minutes	Adequate
Data collection "Air temperature, relative humidity, wind direction and speed, precipitation at Russian Arctic stations"	measurements are performed at 6 h intervals	interval at every 3 h would be more desirable	interval at every 3 h would be more desirable (especially for NWP applications)
Integrated Global Radiosonde Archive (IGRA) (Soundings from Canada, United States, Greenland, Faroe Islands, Norway, and Finland)	Typical temporal resolution of radio soundings is 2 profiles in a day i.e. 12h	4 sounding a day at 00, 06, 12 and 18 UTC, or 2 soundings per day at 00 and 12 UTC	Any of station did not performed soundings 4 times a day for whole year. 20/44 (28/44) stations succeeded perform 2 or more soundings at least 95% (90%) of days in 2017 (based on the soundings archived in IGRA)
Integrated Global Radiosonde Archive (IGRA) (Russia)	Typical temporal resolution of radio soundings is 2 profiles in a day i.e. 12h	4 sounding a day at 00, 06, 12 and 18 UTC, or 2 soundings per day at 00 and 12 UTC	Any of station did not performed soundings 4 times a day. 18/29 (24/29) stations succeeded perform 2 or more soundings at least 95% (90%) of days in 2017 (based on the soundings archived in IGRA)
In situ field campaign profiles of: Atmospheric temperature, relative humidity, wind speed and wind direction	Soundings are typically released 2-4 times daily; occasionally more frequent during high impact weather events	4 sounding a day at 00, 06, 12 and 18 UTC, or 2 soundings per day at 00 and 12 UTC	Sounding profiles from in situ field campaigns generally exceed the minimum temporal resolution requirement of 2 soundings per day
In situ field campaign surface longwave radiation	Fluxes observed every second (1 Hz)	60 min 3 h 12 h	Temporal resolution requirements exceed the goal criteria

In situ field campaign surface shortwave radiation	Fluxes observed every second (1 Hz)	60 sec 10 min 60 h	Temporal resolution requirements exceed the goal criteria
In situ field campaign turbulent heat and momentum fluxes	Heat and momentum fluxes observed at high frequency (10-20 Hz), typcially averaged to 10-30 min	5 min 20 min 60 min	Temporal resolution requirements meet the breakthrough requirements
In situ field campaign cloud mask / cloud fraction	20 s to 10 min	15 min 30 min 3 h	Temporal resolution requirements exceed the goal criteria
In situ field campaign cloud liquid water path	15 s	15 min 60 min 3 h	Temporal resolution requirements exceed the goal criteria
In situ field campaign cloud ice water content	1 min	15 min 60 min 3 h	Temporal resolution requirements exceed the goal criteria
AIRMETH vertical profiles Polar5	N/A	N/A	The temporal resolution depends on the speed of the aircraft. Measurements taken at 100 Hz. Averaging time/distance of fluxes depends on the atmospheric stability.
AIRMETH vertical profiles Helipod	N/A	N/A	As above
FMI Sodankylä AWS	10 min	30 min	Requirements filled.
FMI Sodankylä snow depth stations	10 min	30 min	Requirements filled.
GRUAN	Daily to 4 times daily	Weekly (GRUAN MANAUL)	Exceeded
Polish Polar Station Hornsund (WIGOS 01003)	3h interval since 1978, 1h since 2002, 1 minute interval since 2009	3h	Temporal resolution requirements exceed the goal criteria
Surface meteorological holdings	Synoptic to monthly	Synoptic (CIMO Guide)	Partially met
Atmospheric Trace Gas Mixing Ratios	continuous records, down to 1Hz, usually averaged to 1hr	0.5-1hr	adequate resolution with continuous monitoring
AC-AHC2 stable water isotope measurement stations	continuously with typical averaging to 15min - 1h	15 min 1 h 3h	requirements met

GAW Aerosols	continuous, 5min-1h time resolution	5 min 30 min 1 h	requirements met
ACTRIS cloud properties	continuous, 30 second time resolution	5 min 30 min 1 h	requirements met
IMR-PINRO Ecosystem Survey Wind measurements	Annually in August-September 2004-ongoing	More frequently	Ideally time series had started earlier (but possible to combine with measurements from earlier cruises)
IMR Barents Sea Winter Survey Wind measurements	Annually in January-February 1976-	More frequently	
Aerosol absorption coefficient upgraded	1h	1h	requirement met
Hydrometeor classification upgraded	30 s	1 min	requirement met

Table 21. Timeliness

Data collection	**Timeliness of observations**	**Required timeliness**	**Comparison: observed vs required**
PROMICE AWS data (2m temp, rel.hum., air pressure, wind speed/direction, SW and LW radiation budget)	Data is transmitted on an hourly basis in the summertime and daily in the wintertime	Hourly all the year	It would be an improvement to deliver near real-time data on a fixed hourly schedule all year
Data collection “Air temperature, relative humidity, wind direction and speed, precipitation at Russian Arctic stations”	all observations are available under request as well as readiness of each data collection (included into the PEEX atmosphere observation system) is defined the owners (contacts are listed in questionnaire A) of the measurement stations	data collections need to be available within required standard timeframe for NWP community users; within a month period of time for the climate research community and other users; all data collections should follow FAIR (Findable, Accessible, Interoperable, Reusable) principles on data	Current status: 2) comparison to independent stable measurement or local secondary standard undertaken irregularly (…); 2) validation using external comparator measurements done only periodically and these comparator measurements lack traceability (…); 1) there is no automated quality monitoring in place;

Integrated Global Radiosonde Archive (IGRA) (Soundings from Canada, United States, Greenland, Faroe Islands, Norway, and Finland)	Data are accessible within a day after acquisition		Timeliness requirement from OSCAR (6min, 30min, 6h) is for NWP. This is requirement for submitting soundings to the GTS. This requirements cannot be applied to timeliness when soundings are available for IGRA, because soundings undergo quality checks before they are available in IGRA.
Integrated Global Radiosonde Archive (IGRA) (Russia)	Data are accessible within a day after acquisition		Timeliness requirement from OSCAR (6min, 30min, 6h) is for NWP. This is requirement for submitting soundings to the GTS. This requirements cannot be applied to timeliness when soundings are available for IGRA, because soundings undergo quality checks before they are available in IGRA.
In situ field campaign profiles of: Atmospheric temperature; Atmospheric relative humidity; Atmospheric wind speed; Atmospheric wind direction	Soundings typically accessible within 6 months after acquisition	3 h 6 h 12 h	Soundings from field campaigns do not meet the timeliness requirements. Often field campaigns submit soundings to the GTS in near real-time (within 12 hours of sounding profile). Soundings submitted to GTS then meet the threshold timeliness requirement
In situ field campaign surface longwave radiation	Fluxes typically accessible within 6 to 18 months after acquisition	60 min 3 h 12 h	Timeliness requirements are not met
In situ field campaign surface shortwave radiation	Fluxes typically accessible within 6 to 18 months after acquisition	15 min 30 min 2 h	Timeliness requirements are not met
In situ field campaign turbulent heat and momentum fluxes	Fluxes typically accessible within 6 to 18 months after acquisition	30 days 60 days 200 days	Timeliness requirements generally fail to meet the requirement levels
In situ field campaign cloud mask / cloud fraction	Cloud mask typically accessible within 6 months after acquisition	15 min 30 min 2 h	Timeliness requirements fail to meet the requirement levels
In situ field campaign cloud liquid water path	Cloud liquid water path typically accessible within 6 months after acquisition	15 min 30 min 2 h	Timeliness requirements fail to meet the requirement levels
In situ field campaign cloud ice water content	Cloud ice water content typically accessible within 6 to 18 months after acquisition	15 min 30 min 2 h	Timeliness requirements fail to meet the requirement levels

AIRMETH vertical profiles Polar5	Data are accessible after an unknown period	1 month 2 months 3 months	Timeliness should be improved.
AIRMETH vertical profiles Helipod	Data are accessible after an unknown period	1 month 2 months 3 months	Timeliness should be improved.
FMI Sodankylä AWS	1 day	15 min	Data for research purposes through http://litdb.fmi.fi. For now/forecasting data is disseminated by other means.
FMI Sodankylä Snow depth stations	6 months	15 min	Data for research purposes through http://litdb.fmi.fi.
GRUAN	Mixed – site dependent but generally within 3 hours	Delayed mode	met
Polish Polar Station Hornsund (WIGOS 01003)	All observations are available under request as well as readiness of each data collection	New, real time database would be required	There is no automated quality monitoring in place
Surface meteorological holdings	Data are accessible in real-time	Real-time	met
NIVA Barents Sea FerryBox wind speed/direction and hyperspectral radiance/irradiance	Data are accessible within 6 months after acquisition	Delayed mode	met
Atmospheric Trace Gas Mixing Ratios	Data are accessible after an unknown period	A maximum delay of 1 year would be desirable	part of the dataset are provided with delays >1 year
AC-AHC2 stable water isotope measurement stations	Raw data accessible real-time. Final data accessible after and unknown period	Daily Monthly Yearly	Calibration requires different post-processing with manual intervention. Fully automated calibration possible.
GAW Aerosols	Processed data typically available after a year. In rare cases also real-time data available (but not required by GAW programme).	60 min 1d 1 y	Hardly met. For many applications / services near-real time data is needed. However, for climate applications requirement met.
ACTRIS cloud properties	Processed data typically available within 2 days	60 min 1d 1 y	Not yet met for some real-time applications such data assimilation for NWP. Requirement for monitoring applications
IMR-PINRO Ecosystem Survey Wind measurements	Data are accessible after an unknown period	Within 1 month	Most often not met

IMR Barents Sea Winter Survey **Wind measurements**	Data are accessible after an unknown period	Within 1 month	Most often not met
Aerosol absorption coefficient upgraded	Analysis done years after observations	No time limit for trend analysis	sufficient
Hydrometeor classification upgraded	Can be automated (< 5 min)	Assimilation: < 30 min Evaluation: no time limit	sufficient

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 22. The overall system uncertainty gaps are identified and presented in Table 23.

Table 22. 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**
Integrated Global Radiosonde Archive (IGRA) (Soundings from Canada, United States, Greenland, Faroe Islands, Norway, and Finland)	5	3			3	6
Integrated Global Radiosonde Archive (IGRA) (Russia)	5	2			3	6
Data collection “Air temperature, relative humidity, wind direction and speed, precipitation at Russian Arctic stations”	2	2	1	1	2	1
In situ field campaign profiles of: Atmospheric temperature, relative humidity, wind speed and direction	2	2			2	
In situ field campaign surface longwave radiation	2	2			1	1
In situ field campaign surface shortwave radiation	2	2			1	1
In situ field campaign turbulent heat and momentum fluxes			1	2	1	1
In situ field campaign cloud mask / cloud fraction			1	2	2	
In situ field campaign cloud liquid water path	5	2				5
In situ field campaign cloud ice water content			1	1	2	1
AIRMETH vertical profiles Polar5	2	3			2	4
AIRMETH vertical profiles Helipod	2	3			2	4
FMI Sodankylä AWS	5	6			6	5
FMI Sodankylä Snow depth stations	3	3			2	2
GRUAN	6	5	6	6	6	5
Polish Polar Station Hornsund (WIGOS 01003)	2	2	1	1	2	1
Surface meteorological holdings	2	2	3	1	1	4
NIVA Barents Sea FerryBox wind speed/direction and hyperspectral radiance/irradiance	6	3			2	6
Atmospheric Trace Gas Mixing Ratios	6	6	6	6	6	5
AC-AHC2 stable water isotope measurement stations	2	2	2	1	2	1
GAW Aerosols	2	2			2	1
ACTRIS cloud properties	5	5	3		5	5
IMR-PINRO Ecosystem Survey - Wind measurements	2	2	1	1	1	1
IMR Barents Sea Winter Survey - Wind measurements	2	2	1	1	1	1
Aerosol absorption coefficient upgraded	2	3			5	3
Hydrometeor classification upgraded	5	5				2

Table 23. Uncertainty

Data collection	**Uncertainty of observations**	**Required uncertainty**	**Comparison: observed vs required**
PROMICE AWS data (air temp 2m, rel.hum., air pressure 2m, wind speed/direction, SW and LW radiation budget)	Not available	Table 4 (WMO OSCAR requirements)	Better documentation of uncertainty must be available to users. Albedo is a parameter than can and should be improved
Data collection "Air temperature, relative humidity, wind direction and speed, precipitation at Russian Arctic stations"	Not available		automated quality monitoring of measurements would be desired
Integrated Global Radiosonde Archive (IGRA) (Soundings from Canada, United States, Greenland, Faroe Islands, Norway, and Finland)	Relative humidity: < 3 % (Temp > -40°C) < 10 % (Temp < -40°C) Temperature: < 0.3 K (Surface - 100 hPa) < 0.6 K (100 hPa - 10 hPa) Horizontal wind: < 0.5 m/s (Surface - 10 hPa) (Uncertainty estimates is for Vaisala RS92 and Lockheed Martin LMS-6 based on Intercomparison of High Quality Radiosonde Systems in Yangjiang, China 2010)	Relative humidity: 2 % 5 % 10 % Temperature: 0.5 K 1 K 3 K Horizontal wind: 1 m/s 3 m/s 5 m/s	Vaisala RS92 and Lockheed Martin LMS-6 radiosondes almost meet the goal in the accuracy in temperature and wind speed. Vaisala RS92 or newer Vaisala RS41 and Lockheed Martin LMS-6 was most used radiosonde types in this area in 2017.
Integrated Global Radiosonde Archive (IGRA) (Soundings from Russia)	Not available		
In situ field campaign profiles of: Atmospheric temperature, relative humidity, and wind speed.	Temperature: < 0.3 K (Surface - 100 hPa) < 0.6 K (100 hPa - 10 hPa) Relative humidity: < 3 % (Temp > -40°C) < 10 % (Temp < -40°C) Horizontal wind speed: < 0.5 m/s (Surface - 10 hPa)	Temperature: 0.5 K 1 K 3 K Relative humidity: 2 % 5 % 10 % Horizontal wind: 1 m/s 3 m/s 5 m/s	Temperature, relative humidity and wind speed generally meet the goal uncertainty requirements
In situ field campaign surface longwave radiation	Not available		
In situ field campaign surface shortwave radiation	Not available		
In situ field campaign turbulent heat and momentum fluxes	Not available		
In situ field campaign cloud mask / cloud fraction	Not available		

In situ field campaign cloud liquid water path	25 g m^{-2}	10 g m^{-2} 20 g m^{-2} 50 g m^{-2}	Liquid water path uncertainty nearly achieves the breakthrough requirement
In situ field campaign cloud ice water content	Not available		
FMI Sodankylä AWS: 2m temperature and precipitation	+/- 0.03 C 0,025 mm	Temperature: 0.5 K 0.8 K 2 K Precipitation: 0.5 mm 2 mm 5 mm	Requirements filled.
FMI Sodankylä Snow depth stations: 2m temperature	+/- 0.03 C	0.5 K 0.8 K 2 K	Requirements filled.
AIRMETH vertical profiles Polar5	Limited information on uncertainty arising from systematic and random effects in the measurement	5 m 10 m 15 m	The actual uncertainty should be assessed precisely.
AIRMETH vertical profiles Helipod	Limited information on uncertainty arising from systematic and random effects in the measurement	5 m 10 m 15 m	The actual uncertainty should be assessed precisely.
GRUAN	Fully metrologically traceable to SI and / or community standards (a principle not a number!)	Metrological traceability	Met
Polish Polar Station Hornsund (WIGOS 01003)	WMO standards for meteorological variables	Table 4 (OSCAR requirements)	Requirements filled.
Surface meteorological holdings	Not quantified	Table 4 (OSCAR requirements)	Not quantified, so not met
NIVA Barents Sea FerryBox wind speed/direction and hyperspectral	Limited information on uncertainty arising from systematic and random effects in the measurement	Table 4 (WMO OSCAR requirements)	Not quantified
Atmospheric Trace Gas Mixing Ratios	varies by station	<0.1ppm CO2 <2ppb CH4	WMO standards are met by most stations
AC-AHC2 stable water isotope measurement stations	varies by station	< 5 permil HDO <0.5 permil H218O	Not assessed coherently
GAW Aerosols	Measurements contain high uncertainties and requirements are not accurately defined, nor surveilled	10% 20% 30%	Not quantified for all network
ACTRIS cloud properties	Measurements may contain high uncertainties, but are well characterised and understood	Table 4 (WMO OSCAR requirements)	Met for most products
IMR-PINRO Ecosystem Survey Wind measurements	Measurements contain high uncertainties and requirements are not accurately defined, nor surveilled	0.5 m/s 1 m/s 3 m/s	Not quantified
IMR Barents Sea Winter Survey Wind measurements	Measurements contain high uncertainties and requirements are not	0.5 m/s 1 m/s 3 m/s	Not quantified

	accurately defined, nor surveilled		
Aerosol absorption coefficient upgraded	around 20%	10% 20% 30%	threshold met
Hydrometeor classification upgraded	around 10%	5% 10% 30%	threshold met

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 24. 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 25. 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 24. 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**
Data collection “Air temperature, relative humidity, wind direction and speed, precipitation at Russian Arctic stations”	4	3	4	No
PROMICE AWS data (air temp 2m, rel.hum., air pressure 2m, wind speed/direction, SW and LW radiation budget)	1	3	5	No
Integrated Global Radiosonde Archive (IGRA) (Soundings from Canada, US, Greenland, Faroe Islands, Norway, and Finland)	3	3	4	Yes
Integrated Global Radiosonde Archive (IGRA) (Soundings from Russia)	3	3	4	Yes
In situ field campaign profiles of: Atmospheric temperature; Atmospheric relative humidity; Atmospheric wind speed; Atmospheric wind direction	1	2	3	No
In situ field campaign surface longwave radiation	1	2	3	No
In situ field campaign surface shortwave radiation	1	2	3	No
In situ field campaign turbulent heat and momentum fluxes	1	2	3	No
In situ field campaign cloud mask / cloud fraction	1	2	3	No
In situ field campaign cloud liquid water path	4	3	4	Yes
In situ field campaign cloud ice water content	3	2	3	No
AIRMETH_vertical_profiles_Polar5	3	2	4	No
AIRMETH_vertical_profiles_Helipod	3	2	4	No
FMI Sodankylä AWS	1	3	4	No
FMI Sodankylä Snow depth stations	1	3	4	No
GRUAN	5	5	5	Yes
Surface meteorological holdings	1	5	4	Yes
NIVA Barents Sea FerryBox wind speed/direction and hyperspectral	3	3	4	Yes
Atmospheric Trace Gas Mixing Ratios	3	4	3	Yes
AC-AHC2 stable water isotope measurement stations				
GAW Aerosols	4	2	3	Yes
ACTRIS cloud properties	4	5	5	Yes
IMR-PINRO Ecosystem Survey - Wind measurements	1	2	2	No
IMR Barents Sea Winter Survey - Wind measurements	1	2	2	No

Aerosol absorption coefficient upgraded	4	4	3	Yes
Hydrometeor classification upgraded	5	5	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 25. 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**
PROMICE AWS data (air temp 2m, rel.hum., air pressure 2m, wind speed/direction, SW and LW radiation budget)	4	1	3
Data collection “Air temperature, relative humidity, wind direction and speed, precipitation at Russian Arctic stations”	2	2	2
Integrated Global Radiosonde Archive (IGRA) (Soundings from Canada, United States, Greenland, Faroe Islands, Norway, and Finland)			
Integrated Global Radiosonde Archive (IGRA) (Russia)			
In situ field campaign profiles of: Atmospheric temperature; Atmospheric relative humidity; Atmospheric wind speed; Atmospheric wind direction	1	2	1
In situ field campaign surface longwave radiation	1	2	1
In situ field campaign surface shortwave radiation	1	2	1
In situ field campaign turbulent heat and momentum fluxes	1	2	1
In situ field campaign cloud mask / cloud fraction	1	1	1
In situ field campaign cloud liquid water path	3	2	2
In situ field campaign cloud ice water content	3	2	2
AIRMETH_vertical_profiles_Polar5	1	2	2
AIRMETH_vertical_profiles_Helipod	2	2	2
FMI Sodankylä AWS	1	2	2
FMI Sodankylä Snow depth stations	2	2	2
GRUAN	6	5	6
Surface meteorological holdings	1	2	3
NIVA Barents Sea FerryBox wind speed/direction and hyperspectral	4	5	6
Atmospheric Trace Gas Mixing Ratios	3	3	3
AC-AHC2 stable water isotope measurement stations	2	2	1
GAW Aerosols	3	2	2
ACTRIS cloud properties	4	2	3
IMR-PINRO Ecosystem Survey - Wind measurements	1	1	1
IMR Barents Sea Winter Survey - Wind measurements	1	1	1
aerosol absorption coefficient upgraded	4	4	3
hydrometeor classification upgraded	2		

4.3 Satellite products

In this section, selected atmospheric 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 28 provides general info related to the addressed atmospheric satellite products.

Table 28. Assessed atmospheric satellite products

Satellite Products	Data assessor	Instrument	Platform	Data Centres and Archives	Coordinating Bodies
Cloud fractional cover **Cloud type** **Cloud top temperature** **Cloud top height** **Cloud top pressure** **Cloud optical thickness** **Cloud phase** **Cloud water path**	Devasthale Abhay (SMHI)	AVHRR	NOAA and MetOp	CM-SAF: http://www.cmsaf.eu/EN/Products/AvailableProducts/Available_Products_node.html	CM-SAF
Cloud fractional cover **Cloud type** **Cloud top temperature** **Cloud top height** **Cloud top pressure** **Cloud optical thickness** **Cloud phase** **Cloud water path**	Devasthale Abhay (SMHI)	AVHRR	NOAA and MetOp	ESA Cloud-CCI project: http://www.esa-cloud-cci.org/	ESA
Data from AIRS hyperspectral IR-sensor	Joseph Sedlar, (MISU)	AIRS (Atmospheric Infrared Sounder)	Aqua	NASA Jet Propulsion Laboratory (JPL) https://airs.jpl.nasa.gov	NASA JPL
Integrated Water Vapor	Georg Heygster (UB)	AMSR-E, AMSR2, AMSU-B, MHS	AQUA, GCOM-W, NOAA, METOP	University of Bremen, Institute of Environmental Physics (seaice.uni-bremen.de)	UB

4.3.2 Gaps in spatial and 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 29, spatial vertical and horizontal coverage (i.e. measurement locations) of each data collection is compared with the corresponding requirements. In Table 30, spatial vertical and horizontal resolution of each data collection is compared with the corresponding requirements. In Tables 31 and 32 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 21 presents the data collections timeliness (i.e. how fast the data become available after collection).

Table 29. Spatial coverage

Product	**Horizontal coverage of observations**	**Vertical coverage of observations**	**Required horizontal coverage**	**Required vertical coverage**	**Comparison: observed vs required**
AIRS surface and upper atmospheric temperature	1° x 1° (Level 3)	Standard atmospheric pressure levels: 1000, 925, 850, 700, 600, 500, 400, 300 hPa	100 km 200 km 500 km	Lower troposphere, higher troposphere requirements 0.1 km 0.2 km 0.5 km	Spatial coverage generally exceeds the goal required horizontal coverage. AIRS Level 3 tropospheric temperature profiles are provided on 8 standard pressure levels and therefore the required vertical coverage is not met.
AIRS surface and upper atmospheric water vapor mixing ratio	1° x 1° (Level 3)	Standard atmospheric pressure levels: 1000, 925, 850, 700, 600, 500, 400, 300 hPa	10 km (LT) 15 km (LT) 25 km (LT) 20 km (HT) 50 km (HT) 100 km (HT)	0.1 km (LT, HT) 0.5 km (LT, HT) 2 km (LT, HT)	Level 3 horizontal coverage fails to meet the requirements in the lower troposphere, but meets the threshold requirement in the higher troposphere. AIRS Level 3 tropospheric water vapor mixing ratio profiles are provided on 8 standard pressure levels and therefore the required vertical coverage is only met at the threshold level.
Cloud fraction	0.25° x 0.25° (CM-SAF, L3) 0.5° x 0.5° (ESA CCI, L3)	Total column	50 km 100 km 250 km	N/A	CM-SAF and ESA CCI horizontal coverages meet the requirements.
Cloud top properties	0.25° x 0.25° (CM-SAF, L3) 0.5° x 0.5° (ESA CCI, L3)	Total column	50 km 100 km 250 km	N/A	CM-SAF and ESA CCI horizontal coverages meet the requirements.
Cloud liquid and ice water contents	0.25° x 0.25° (CM-SAF, L3) 0.5° x 0.5° (ESA CCI, L3)	Total column	50 km 100 km 250 km	N/A	CM-SAF and ESA CCI horizontal coverages meet the requirements.

Integrated Water Vapor upgraded	35°N to 90°N	Total column	Global ocean	N/A	Met requirements

Table 30. Spatial resolution

Product	**Horizontal resolution of observations**	**Vertical resolution of observations**	**Required horizontal resolution**	**Required vertical resolution**	**Comparison: observed vs required**
AIRS surface and upper atmospheric temperature	1° x 1° (Level 3)	Standard atmospheric pressure levels: 1000, 925, 850, 700, 600, 500, 400, 300 hPa	100 km 200 km 500 km	Lower troposphere, higher troposphere requirements 0.1 km, 0.2 km, 0.5 km	Spatial resolution generally exceeds the goal required horizontal coverage. AIRS Level 3 tropospheric temperature profiles are provided on 8 standard pressure levels and therefore the required vertical resolution is not met. AIRS Level 3 footprint is approximately 40x40 km. These footprints are concatenated into the 1° x 1° gridded Level 3 horizontal resolution.
AIRS surface and upper atmospheric water vapor mixing ratio	1° x 1° (Level 3)	Standard atmospheric pressure levels: 1000, 925, 850, 700, 600, 500, 400, 300 hPa	10 km (LT) 15 km (LT) 25 km (LT) 20 km (HT) 50 km (HT) 100 km (HT)	0.1 km (LT, HT) 0.5 km (LT, HT) 2 km (LT, HT)	Level 3 horizontal coverage fails to meet the requirements in the lower troposphere, but meets the threshold requirement in the higher troposphere. AIRS Level 3 tropospheric water vapor mixing ratio profiles are provided on 8 standard pressure levels and therefore the required vertical coverage is only met at the threshold level. AIRS Level 3 footprint is approximately 40x40 km. These footprints are concatenated into the 1° x 1° gridded Level 3 horizontal resolution.
Cloud fraction	0.25° x 0.25° (CM-SAF, L3) 0.5° x 0.5° (ESA CCI, L3)	Total column	50 km 100 km 250 km	N/A	CM-SAF and ESA CCI spatial resolutions meet the requirements.
Cloud top properties	0.25° x 0.25° (CM-SAF, L3) 0.5° x 0.5° (ESA CCI, L3)	Total column	50 km 100 km 250 km	N/A	CM-SAF and ESA CCI spatial resolutions meet the requirements.
Cloud liquid and ice water paths	0.25° x 0.25° (CM-SAF, L3) 0.5° x 0.5° (ESA CCI, L3)	Total column	50 km 100 km 250 km	N/A	CM-SAF and ESA CCI spatial resolutions meet the requirements.
Integrated Water Vapor upgraded	12.5 km	Total column	15 km 50 km 250 km	N/A	Met requirements

Table 31. Temporal coverage

Product	Temporal coverage of observations	Required temporal coverage	Comparison: observed vs required
AIRS surface and upper atmospheric temperature	2003-01-01 to 2016-08-31	N/A	Temporal coverage analyzed were chosen when the instrument was in mature operation. During September 2016, the microwave sounding unit AMSU malfunctioned and was removed from the combined IR-microwave joint thermodynamic product. From September 2016 to present, only AIRS IR brightness temperatures are utilized to retrieve atmospheric thermodynamic profiles.
AIRS surface and upper atmospheric water vapor mixing ratio	2003-01-01 to 2016-08-31	N/A	Temporal coverage analyzed were chosen when the instrument was in mature operation. During September 2016, the microwave sounding unit AMSU malfunctioned and was removed from the combined IR-microwave joint thermodynamic product. From September 2016 to present, only AIRS IR brightness temperatures are utilized to retrieve atmospheric thermodynamic profiles.
Cloud fraction	1982-01-01 to 2015-12-31 (CM-SAF) 1982-01-01 to 2014-12-31 (ESA CCI)	N/A	Temporal coverages here refer to the AVHRR based datasets. These datasets undergo periodic updates and extensions.
Cloud top properties	1982-01-01 to 2015-12-31 (CM-SAF) 1982-01-01 to 2014-12-31 (ESA CCI)	N/A	Temporal coverages here refer to the AVHRR based datasets. These datasets undergo periodic updates and extensions.
Cloud liquid and ice water paths	1982-01-01 to 2015-12-31 (CM-SAF) 1982-01-01 to 2014-12-31 (ESA CCI)	N/A	Temporal coverages here refer to the AVHRR based datasets. These datasets undergo periodic updates and extensions.
Integrated water vapor upgraded	2006-2010; 2017 (tbc)	N/A	N/A

Table 32. Temporal resolution

Product	**Temporal resolution of observations**	**Required temporal resolution**	**Comparison: observed vs required**
AIRS surface and upper atmospheric temperature	Daily Level 3 surface temperature and tropospheric profiles of temperature. Twice daily overpasses at approximately 01:30 (descending orbit) and 13:30 (ascending orbit) local time. These have been averaged to produce daily mean surface and tropospheric temperature profiles.	3 h 4 h 6 h	Observed temporal resolution is limited by the polar orbit of Aqua, and therefore the requirements on temporal resolution are not met.
AIRS surface and upper atmospheric water vapor mixing ratio	Daily Level 3 surface and tropospheric profiles of water vapor mixing ratio. Twice daily overpasses at approximately 01:30 (descending orbit) and 13:30 (ascending orbit) local time. These have been averaged to produce daily mean surface and tropospheric water vapor mixing profiles.	3 h 4 h 6 h	Observed temporal resolution is limited by the polar orbit of Aqua, and therefore the requirements on temporal resolution are not met.
Cloud fraction	L2B datasets from both CM-SAF and ESA CCI are available twice daily	3 h 6 h 12 h	The Sun-synchronous orbit of the NOAA and MetOp satellites allow only twice daily observations
Cloud top properties	L2B datasets from both CM-SAF and ESA CCI are available twice daily	3 h 6 h 12 h	The Sun-synchronous orbit of the NOAA and MetOp satellites allow only twice daily observations
Cloud liquid and ice water paths	L2B datasets from both CM-SAF and ESA CCI are available once daily	3 h 6 h 12 h	The Sun-synchronous orbit of the NOAA and MetOp satellites and retrieval dependence on solar channels allow only once daily observations
Integrated water vapor upgraded	24 h	1 h 6 h 12 h	Not met requirements

4.3.3 Gaps in timeliness

This section analyses the timeliness of data collections. The requirements are set for each data collection in Sect. 3. Table 33 presents the data collections timeliness (i.e. how fast the data become available after collection).

Table 33. Timeliness

Product	Timeliness of observations	Required timeliness	Comparison: observed vs required
AIRS surface and upper atmospheric temperature	Data accessible within 1 month after acquisition	3 h 6 h 12 h	Processing and quality control measures by the AIRS science team limit the thermodynamic profiles of AIRS in meeting the timeliness requirements
AIRS surface and upper atmospheric water vapor mixing ratio	Data accessible within 1 month after acquisition	7 d 14 d 60 d	Processing and quality control measures by the AIRS science team result in water vapor mixing ratio profile timeliness to achieve the threshold requirement
Cloud fraction	CM-SAF and ESA CCI datasets accessible only for the stated temporal coverage	N/A	The datasets undergo periodic revisions and extensions. CM-SAF datasets are updated under the framework of 5-year continuous development phases, but ESA-CCI has no such commitment.
Cloud top properties	CM-SAF and ESA CCI datasets accessible only for the stated temporal coverage	N/A	The datasets undergo periodic revisions and extensions. CM-SAF datasets are updated under the framework of 5-year continuous development phases, but ESA-CCI has no such commitment.
Cloud liquid and ice water paths	CM-SAF and ESA CCI datasets accessible only for the stated temporal coverage	N/A	The datasets undergo periodic revisions and extensions. CM-SAF datasets are updated under the framework of 5-year continuous development phases, but ESA-CCI has no such commitment.
Atmospheric total water vapor upgraded	24 h	6 min 30 min 6 h	Not met requirements

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.

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 34. The overall system uncertainty gaps are identified and presented in Table 35.

Table 34. 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**
AIRS surface and upper atmospheric temperature	3	6	2	5
AIRS surface and upper atmospheric water vapor mixing ratio	3	6	2	5
CM-SAF and ESA CCI Cloud fraction	3	6	4	5
CM-SAF and ESA CCI Cloud top properties	3	6	4	5
CM-SAF and ESA CCI Cloud liquid and ice water paths	3	4	2	4
Atmospheric total water vapor upgraded	2	3	2	1

Table 35. Gap in uncertainty

Product	**Uncertainty of observations**	**Required uncertainty**	**Comparison: observed vs required**
AIRS surface and upper atmospheric temperature	1° Kelvin per 1 km thick layer	0.5 K 1 K 2 K	The stated uncertainty in AIRS Level 3 temperature meets the breakthrough requirement threshold. Analysis of daily mean temperatures relative to radiousoundings indicates generally large biases in the lower troposphere which exceed the stated uncertainty.
AIRS surface and upper atmospheric water vapor mixing ratio	15% per 2 km thick layer	2 % (HT) 5 % (HT) 20 % (HT) 2 % (LT) 4 % (LT) 15 % (LT)	The stated uncertainty in AIRS Level 3 water vapor mixing ratio meets the threshold requirements. Analysis of daily mean water vapor mixing ratios relative to radiosoundings indicates generally large biases in the lower troposphere which exceed the stated uncertainty.
Cloud fraction	-3.2% 40% -1.3%	5% 20% 2%	CM-SAF CLARA-A2 satellite dataset, validation report Requirements on accuracy, precision and stability per decade resp. Accuracy and stability requirements are met globally.
Cloud top height	-840 m 2380 m N/A	800 m 1700 m 200 m	CM-SAF CLARA-A2 requirements on accuracy, precision and stability per decade resp. Cloud top height requirements are generally not met, except for the optically thick clouds
Cloud liquid water path	-3.5 to 4.3 gm^{2} 11 to 20 gm^{2} 1.0 to 2.3 gm^{2}	10 gm^{2} 20 gm^{2} 3 gm^{2}	CM-SAF CLARA-A2 requirements on accuracy, precision and stability per decade resp. LWP requirements are met in the mid latitudes and the tropics, but generally not in the Arctic.
Cloud ice water path	0.6 to 5.1 gm^{2} 20 to 24 gm^{2} 2.7 to 3.7 gm^{2}	20 gm^{2} 40 gm^{2} 6 gm^{2}	CM-SAF CLARA-A2 requirements on accuracy, precision and stability per decade resp. IWP requirements are met in the mid latitudes and the tropics, but generally not in the Arctic.
Atmospheric total water vapor upgraded	3 kg/m^{2}	1 kg.m^{-2} 2 kg.m^{-2} 5 kg.m^{-2}	Not met goal or breakthrough requirement

4.3.5 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 36. 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 37. 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 (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 (pixel, grid point, etc.) level metadata along with unique measurement set metadata
6. As in (5) + Complete location (pixel, grid point, etc.) 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 36. 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 three options.

Product	**Standards**	**Collection level metadata**	**File level metadata**	**Quality flags**
AIRS surface and upper atmospheric temperature	4	3	4	Yes
AIRS surface and upper atmospheric water vapor mixing ratio	4	3	4	Yes
Cloud fraction, CM.SAF and ESA CCI	4	4	5	Partly
Cloud top properties, CM.SAF and ESA CCI	4	4	5	Partly
Cloud liquid and ice water paths, CM.SAF and ESA CCI	3	4	4	Partly
Atmospheric total water vapor upgraded			2	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 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 37. 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**
AIRS surface and upper atmospheric temperature	5	4	6
AIRS surface and upper atmospheric water vapor mixing ratio	5	4	6
Cloud fraction, CM-SAF and ESA CCI	5	5	6
Cloud top properties, CM-SAF and ESA CCI	5	5	6
Cloud liquid and ice water paths, CM-SAF and ESA CCI	5	5	6
Atmospheric total water vapor upgraded	3	3	1

4.3.6 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 data record and version control are assessed for each data collection and classified on a scale from 1 to 6 (Table 38). 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 38. 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**
AIRS surface and upper atmospheric temperature	4	5	5	5	6
AIRS surface and upper atmospheric water vapor mixing ratio	4	5	5	5	6
Cloud fraction, CM-SAF and ESA CCI	5	5	5	4	6
Cloud top properties, CM-SAF and ESA CCI	5	5	5	4	6
Cloud liquid and ice water paths, CM-SAF and ESA CCI	5	5	5	4	6
Atmospheric total water vapor upgraded	2	6	2	2	2

5. Recommendations

In this section we provide recommendations from each partner relative to the observation systems that have been assessed in this document. At the end we also merge this with recommendations from Deliverable D2.5 on Updated Data Products.

One result of this assessment is the recognition of many surface-based observation systems that exists but were designed for other purposes, but that also carry out atmospheric observations. These could be better utilized in INTAROS by making them more readily available both for scientific purposes, for climate monitoring and for operational weather forecasting.

However, it is also clear that there is a severe lack of all types of atmospheric observations over the Arctic Ocean. This is in particular the case when it comes to observations of the vertical structure of the atmosphere. While this could be somewhat alleviated of ascertaining that radiosounding observations are taken during more shipping activities, commercial as well as scientific, a real solution to this problem probably have to rely on either airborne dropsondes networks or satellite sensors. In this context a main recommendation is that satellite sensor development target the special requirements that pertains to the Arctic, where the cloudiness is high, absolute moisture relatively low and the atmospheric boundary layer is very shallow. This needs to address both spatial coverage, sensor integration (passive and active) and vertical resolution.

Finally, it needs to be recognized that satellite retrievals always rely on so-called a priori information; this is often taken from atmospheric models, either operational models or reanalysis. While it is well known that these models often fail to describe the details of the Arctic atmosphere, it becomes clear model improvement is essential. Such model improvement must be based on an improved understanding of various processes especially relevant to the Arctic. This in turn means that there has to be more research-grade observations, that usually only comes from short icebreaker-based field campaigns. This means there needs to be a common concerted international effort to increase the activity in this respect, in time and spatial coverage.

5.1 UiB

5.1.1 Stable water isotopes

In order to monitor transport of water vapour isotopes into the Arctic through the North Atlantic and Pacific storm track, we recommend closing gaps in the station network in eastern Scandinavia as a matter of high priority. Deployment of measurement instrumentation on ice going vessels and during aircraft campaigns will also help further in closing the Arctic moisture budget using isotope measurements. Long-terms financial and maintenance support of key measurement sites in the North-Atlantic storm track needs to be secured.

5.2 IMR

5.2.1 Ship-based temperature and wind speed from IMR-PINRO Ecosystem Survey and Barent Sea winter study

The basic meteorological observations data were collected during cruises that aimed to gather marine data needed to provide advice for fisheries (and to a certain degree environmental) management. Hence, the survey design, including geographical and temporal coverage, is not linked to atmospheric monitoring. However, the surveyed Arctic areas are very relevant also from a meteorological perspective. Presently, wind and temperature observations are not linked to or searchable from atmospheric related portals, and therefore they have so far not been used by the atmospheric community. We recommend a better visibility of those data in Arctic portals, as the one that will be created in INTAROS for the integrated Arctic Observing System (iAOS).

5.3 MISU

5.3.1 Evaluating thermodynamic structure from AIRS satellite information

AIRS thermodynamic profiles provide an unprecedented record of the thermodynamic state of the troposphere across the full Arctic domain. Because of this consistent, long running data record, we highly recommend the use of AIRS thermodynamic profiles across the Arctic. In particular, we support the usage of AIRS thermodynamic measurements across the mid- to upper-troposphere (600 - 300 hPa). Additionally, based on the accuracy in the AIRS - radiosounding evaluation across the Arctic troposphere, we recommend the usage of AIRS measurements for climatological, anomalies and atmospheric thermodynamic transport studies.

However, we also have highlighted complications in the accuracy of AIRS thermodynamics observations throughout the lower Arctic troposphere (700 - 1000 hPa). In particular, AIRS lower tropospheric temperature and humidity structures are consistently the least accurate and contain of the largest mean bias and root mean squared errors relative to the rest of the troposphere. These errors are shown to cause artificial thermodynamic stability structures, which are critically important for process-level studies and understanding; the relatively poor vertical resolution of AIRS L3 thermodynamics contributes to these artificial gradients in lower tropospheric structure, especially because low level clouds over the Arctic are ubiquitous.

We recommend therefore that efforts are placed on AIRS cloud-clearing processing to improve thermodynamic retrievals through cloudy satellite footprints. Likewise, efforts to improve radiance weighting functions may improve the vertical resolution of AIRS thermodynamic profiles, especially across the lower troposphere.

5.3.2 Atmospheric observations from central Arctic field campaigns

Intensive in situ field campaigns provide the scientific community with detailed, high frequency measurements of the full Arctic troposphere, cloud properties and the surface energy budget components; this type of data are likely underutilized. We therefore highly recommend the usage of field campaign measurements for improving fundamental, process-level understanding of the Arctic atmosphere and the interactions among processes operating on varying scales. These measurements provide an unprecedented baseline for evaluation of satellite-borne measurements and numerical model simulations. We recommend that concerted efforts are established on an international level to sustain frequent and regular in situ field campaigns in the central Arctic Ocean that span also the winter season.

5.4 AU

5.4.1 Greenland Ecosystem Monitoring Programme

The sustained logistic and scientific framework associated with the GEM programme provide an important “hub” where additional data can be collected with minimal extra cost. Also, the GEM programme must continue to meet community standards as they continue to be defined. A specific aim formulated in the GEM strategy for 2017-2021 is to develop methods and products that improve the capability of the programme to upscale knowledge from local scale measurement to larger regions of Greenland, which relies strongly on utilizing current remote sensing products.

5.5 GEUS

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

The meteorological variables collected at the automatic weather stations in the PROMICE network on the Greenland ice sheet are currently under-utilized by the meteorological community. To alleviate some of the difficulty in the use of the PROMICE AWS data it is recommended to increase the temporal coverage to hourly transmissions through the whole year. We also recommend to increase the precision of the positioning of the AWS to allow the meteorological variables to live up to current requirements of WMO, particularly for barometric pressure. Recommendations regarding other parameters would be to prepare to monitor the expected transition in the Arctic of precipitation going from solid to liquid. This implies mounting instruments to monitor SWE (snow water-equivalent) as well as rain on the AWSs in the lower part of the ablation zone of the Greenland ice sheet, particularly in the southernmost locations where the transition is believed to happen first. This will allow the network to monitor the onset of a likely new feedback effect that will potentially accelerate the contribution of the Greenland ice sheet to sea level rise. It will be increasingly important to provide in-situ ground control for satellite-derived parameters, e.g. of the Copernicus programme. Albedo is an example of such a parameter which can be prioritized for ground-truthing satellite-derived products.

5.5.2 The Greenland Climate Network

A recommendation for the GC-Net would be an upgrade of the radiation instrumentation on the stations. This would allow GC-Net to provide highly useful and much needed albedo measurements for validation and calibration of satellite-derived albedo products, e.g from the Sentinel-programme.

In terms of spatial coverage, there is an under-representation of stations in the Southeast Greenland part of the ice sheet where the precipitation is high and storms are frequent. The combination of harsh environmental conditions for the stations and difficult logistics makes this a challenging region to instrument, but it is also the part of the ice sheet with the highest variability in mass balance.

5.6 FMI

5.6.1 Radiosonde sounding network and Integrated Global Radiosonde Archive

Radiosonde soundings provide detailed profiles of atmospheric temperature, humidity, wind speed and wind direction. The accuracy of observation generally fulfill the requirements in the cases in which the estimates of uncertainty of radiosondes is available. However, uncertainty estimates for all radiosonde types is not available. We therefore recommended that the documentation of uncertainty should be improved for the different radiosonde types for which uncertainty estimates are not currently available.

5.6.2 Long-term surface-based atmospheric composition measurements

The main benefits of GAW programme are the vast variety of atmospheric parameters covered in a global scale. Data distribution and guidelines for measurements are well organized, recognized and functional, though requirements are not always strictly defined. The importance of focused networks for improving and surveilling the data quality and for the long-term sustainability is highlighted. The largest gaps in GAW Aerosol programme at the moment are in data quality and in geographical coverage. Data series are still relatively short and thus, we recommend that focus should be put on securing their continuation. It is worth mentioning that European ACTRIS research infrastructure is expected to improve these recognized gaps and needs in near future. However, the ACTRIS network only covers the European side of the Arctic which is geographically insufficient.

5.6.3 Integrated Carbon Observation System (ICOS)

ICOS provides coordinated and harmonised in-situ measurements of greenhouse gases and fluxes at the surface and, crucially, has long-term support. Together with other networks (tall-tower, eddy-covariance), and ship-based measurements, pan-Arctic coverage is realised although spatially sparse. It is clear that regular ocean measurements must continue to maintain the long-term time-series necessary to provide trends. We recommend that understanding the spatial representativeness of current locations is key in deciding future potential sites for the network.

5.6.4 Aerosol, Clouds and Trace gases infrastructure (ACTRIS)

ACTRIS provides comprehensive in-situ and vertical profiling of aerosol, clouds, and trace gases; hence, together with ship-borne campaigns with similar instrumentation, has the capability of providing the measurements necessary to validate and extend a wide variety of both satellite and surface-based products, albeit at a limited number of locations. ACTRIS has long-term support, and although the ACTRIS remit is largely confined to European-operated stations, this does not limit the geographical location of stations to Europe. The logistics and manpower required to operate ACTRIS stations limit their spatial coverage, and choice of location, especially in the Arctic. However, together with similarly instrumented stations in Alaska and Canada, a few ACTRIS sites can provide the detailed information required to enable exploitation of denser networks of much cheaper but less capable instrumentation, and anchor satellite retrievals. An additional station hosted by Russia would be the obvious recommendation to begin filling the large gaps in Arctic coverage for the parameters measured by ACTRIS.

5.6.5 Meteorological observations at Sodankylä

FMI AWS and snow depth stations are part of the Sodankylä-Pallas satellite cal/val station. The station is maintained and developed as one of FMI’s most important focus points. Temporally there are no large gaps in the air temperature time series since 1908. The spatial coverage of the measurements is limited, but the measurements are part of network covering the whole Finland. The time series of air temperature from snow depth stations is very short, but its purpose is to support other measurements installed at the same time.

5.7 SMHI

5.7.1 Satellite observations of cloud parameters

Based on the intercomparison of various cloud climatologies, evaluations with different observational systems, the following recommendations can be proposed. a) Key observational gaps remain during polar night. The quality of cloud property retrievals degrades significantly during nearly six dark months of a year. Future space based missions should factor in possibilities to address this challenge, by carrying out detailed information content analysis during the design and channel selection stages of the mission, focusing particularly on the Arctic conditions. b) Future missions should also strive for improving the quality of cloud microphysical property retrievals during summer and explore feasibility to derive those during polar night, by further exploiting synergy between active (e.g. lidar and radar) and passive thermal observations (e.g. hyperspectral). c) Almost all cloud property retrieval algorithms require ancillary information, such as from reanalysis datasets. The quality of these historical reanalysis data can change dramatically over the Arctic with time. This has an impact on the stability of derived products. The future reprocessing efforts shall elaborately take this limitation into account.

5.8 NUIM

5.8.1 GCOS Reference Upper Air Network (GRUAN)

GRUAN would benefit most from the qualification and provision of additional measurement streams (lidar, MWR, frostpoint hygrometers) which would serve to augment temporal coverage and build confidence in the verity of the radiosonde measurement series and their uncertainty. With the transition to RS41 sondes from Vaisala, GRUAN needs to undertake robust change management and share the resulting knowledge with radiosonde stations from GUAN and GOS. Geographically, GAIA-CLIM has shown GRUAN coverage in the Arctic to be sufficient for satellite characterization. However, there are several other potential application areas and a similar consideration for these may yield gaps. It should be stressed that GRUAN is not and cannot be intended to provide spatio-temporally rich information. Most logically if an additional station were required it would likely need to be hosted by Russia.

2.8.2 GOS surface metrological observations

Development of a global set of integrated holdings is ongoing in parallel to INTAROS. First and foremost, it is important that C3S and NOAA NCEI continue this critical activity through to fruition. This may take well in excess of a decade. For actors in the Arctic domain it is critical that all existent data be shared. This includes non-digital records which C3S are also undertaking to rescue. Looking forwards, current station configurations in many parts of the Arctic fail to meet stipulated requirements laid forth by WMO in particular for spatial resolution for most of the surface meteorological parameters. The Arctic is a difficult place to measure and it is unclear to what extent global requirements map down to regional requirements for the Arctic domain. On the flip side, increasing automation may allow remote observations in a cost-effective manner.

5.9 MPG

5.9.1 Greenhouse gas flux measurements from tall towers

The current network of sites spans the whole Arctic, with adequate temporal resolution and excellent data quality. A large share of the observations is made available online with only minor delays, while other parts are available upon request with the PIs. The network overall is still rather sparse, and particularly in the Siberian domain larger gaps exist; therefore, the addition of new sites would significantly strengthen the network. Data sharing on a common online platform, in combination with clear statements by site PIs when data will be made available, would further strengthen network-wide synthesis activities.

5.10 NIVA

5.10.1 Barents Sea FerryBox

Wind speed and direction, and hyperspectral radiance/irradiance observations are important variables for interpretation of air-sea gas exchange and oceanic inherent optical properties, respectively. While more observations and minimizing uncertainty are desirable, FerryBox systems are by definition limited to the ship operation since they are using ships of opportunity. If possible, we recommend expanding ship of opportunity based observations to increase spatial and temporal coverage in the Arctic. In addition, uncertainty estimates should be documented accordingly.

5.11 U Helsinki

5.11.1 Pan-Eurasian Experiment (PEEX)

The continuous long-term meteorological observations in the Arctic region for basic meteorology (temperature, humidity, wind, precipitation-related characteristics) in the surface layer of the atmosphere allows to identify spatio-temporal variability in heat-moisture-momentum regimes in a rapidly changing climatic conditions 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 trends in a changing climate, for verification (and hence, improvement) of the operational numerical weather prediction models at multi-scales and refining 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.

5.12 GFZ

5.12.1 Airborne trace gas profiles - campaign setup, instrumentation and examples

We recommend using the data from vertical profile flights not only to gain spatial information on atmospheric boundary layer height and composition, but also to validate transport simulations in the Arctic. This could help us gain unprecedented insights in atmospheric transport processes in the Arctic.

5.13 IGPAN

5.13.1 Polish station Hornsund

The Polish Polar Station Hornsund located on the northern shore of the Hornsundfjord on Wedel Jarlsberg Land in SW Spitsbergen. Warm and humid air transported by extratropical cyclones from lower latitudes and warm West Spitsbergen current have significant influence on the climate, which is mild and maritime, with respect to its high latitude. Long term meteorological monitoring started at Hornsund Station in 1978 gives an opportunity to understand regional climate change, that directly affects the local climate on a temporal scale. Analyses of climate variability and trends on local scales are key in understanding and predicting the sensitivity of high-latitude ecosystems.

5.14 Recommendations for upgraded data products – from D2.5

5.14.1 Upgraded aerosol absorption coefficient

Full uncertainty analysis for the Arctic aethalometer data and a systematic inter-comparison with reference instruments was done for a 3-year dataset of aerosol absorption coefficient (available at: http://actris.nilu.no/Content/?pageid=39a25e967ef3481b8152f654434c258c). A new analysis method reduced earlier data uncertainty due to electronic noise and the intercomparison led to more harmonized data series. Improvement was achieved, with respect to original data in GAW Aerosol database, also in data and metadata documentation and description of scientific methodologies.

5.14.2 Upgraded ceilometer products

Identification of liquid layers in ceilometer profiles, including supercooled liquid in the presence of ice (mixed-phase cloud), has already been demonstrated in an operational context, but full assessment of the ceilometer hydrometeor classification product over Arctic stations is still necessary, especially for robust diagnosis of the precipitation classes. Standard operating procedures and data processing are required to enable harmonized products.

Data coverage would be improved markedly with minimum effort by obtaining profile data from more ceilometers currently operating in the Arctic but not yet recording the full attenuated backscatter profile.

5.14.3 Upgraded Integrated Water Vapor from satellites

The new satellite based total water vapor (TWV) product developed in INTAROS fills a gap since continuous TWV values over ocean and sea ice have not been available before. The achieved horizontal resolution exceeds the OSCAR requirements. The required uncertainty of 1 kg/m^2 is not met in all cases. However, at the typical, low WV values met in the Arctic this threshold is frequently achieved.

The usefulness of the resulting data set for offline investigations will be demonstrated in the analysis of spatial and temporal distribution of greenhouse gases planned in WP 3, Task 3.5. The required TWV data set will be completed in due time, coordinated with WP 3.

The temporal resolution and timeliness for operational applications according to the OSCAR tables are not met. However, they can be improved by processing instead of daily averages, single swathes (overflights) from the two involved sensors.

Then, for combining the data from the two sensors, the gap in overflight times needs to be taken into account. First steps to improve the timeliness of a combined data product can be investigating the coverage by the two sensors in 12 h and 6 h periods and to see how well these two coverages complement and overlap. Another possibility to improve temporal resolution and timeliness is processing single swathes and to exploit the synergy of the two sensors in the assimilation step of the used NWP model.

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A2.3. Appendix

A2.3.1. Radiosoundings used for AIRS evaluation

Table A1. Radiosounding observatories, geographic coordinates, temporal period used for evaluation, the sounding launch frequency per day and associated radiosounding network.

Site	Coordinates	Time period for evaluation	Launch frequency	Associated Network
Barrow, AK (ARM-NSA)	71.3°N 156.6°W	January 2003 to August 2016	1-2 per day	GRUAN
Tiksi, Russia	71.6°N 128.9°E	January 2003 to August 2016	1-2 per day	IGRA
Ny-Ålesund, Svalbard	78.9°N 11.9°E	January 2003 to August 2016	1-2 per day	GRUAN
ASCOS	77.9°N - 87.5°N 11.1°W - 9.6°E	August 2008 to September 2008	4 per day	In-situ field campaign
ACSE	71.4°N - 85.2°N 25.7°E - 178.1°W	July 2014 to October 2014	4 per day	In-situ field campaign
N-ICE	79.2°N - 83.3°N 3.4°E - 29.8°E	January 2015 to June 2015	2 per day	In-situ field campaign
Sea State	65.9°N - 75.5°N 148.6°W - 168.5°W	October 2015 to November 2015	4 per day (intermittently more frequent)	In-situ field campaign
Polarstern	See Fig. 2.4.1	June to October for years: 2007, 2008, 2009, 2010, 2011, 2012, 2014	1-2 per day	In-situ field campaigns

A2.3.2. Seasonal AIRS-radiosounding vertical error distribution and error statistics

Seasonal error distributions in T and Q for AIRS minus radiosounding thermodynamics are shown for Tiksi (Fig. A1) and Ny-Ålesund (Fig. A2); error distributions for all central Arctic field campaigns are combined and shown in Fig. A3. The seasonal variability in the error distributions are similar amongst all the observation sites. AIRS mid- to upper tropospheric thermodynamics differences to soundings are generally symmetrical around near zero, also where MBE and RMSE are smallest. AIRS error distributions generally increase in spread and are often skewed in the lower troposphere and especially close to the surface. The AIRS dry bias in the lower troposphere is consistent among all observatories and for all seasons, except very near the surface during winter and autumn at Ny-Ålesund (Fig. A2b). During summer, T

RFDs show a dominant peaks nearest the surface indicating a relatively large cold bias (peaks at or below -4 K) at Tiksi and Ny-Ålesund (Figs. A1-A2); the RFDs from Barrow (Fig. 6) and the field campaigns (Fig. A3) are more uniform and contain relative maxima slightly above 0 K error. The RFDs of summer Q from all observatories indicate a large spread in AIRS water vapor below 600 hPa relative to radiosoundings.

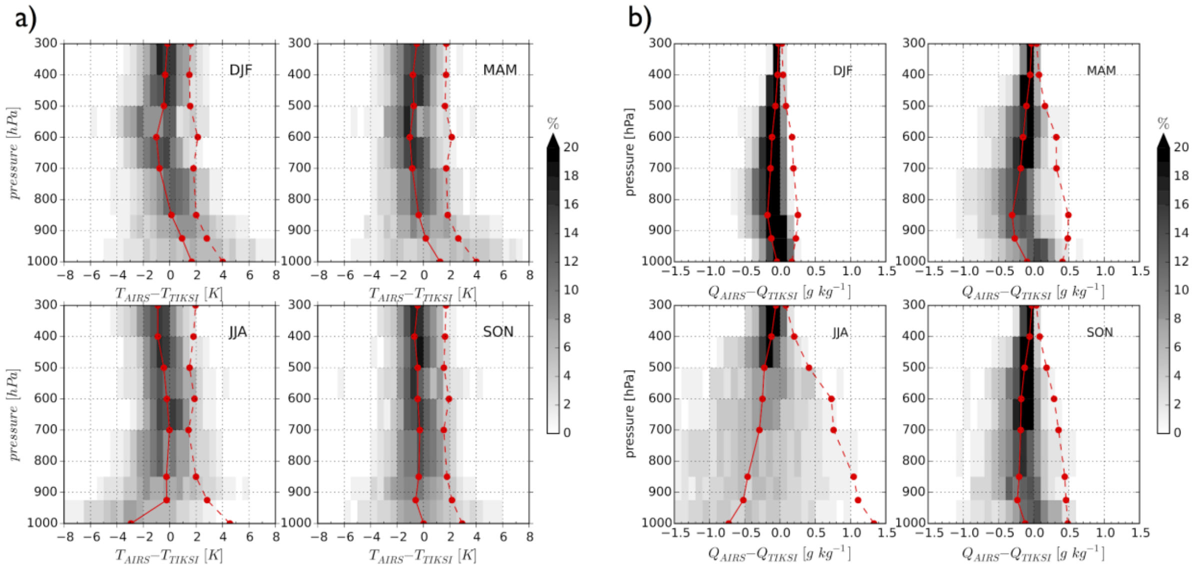

Figure A1. Same as in Fig. 6, but for Tiksi, Russia.

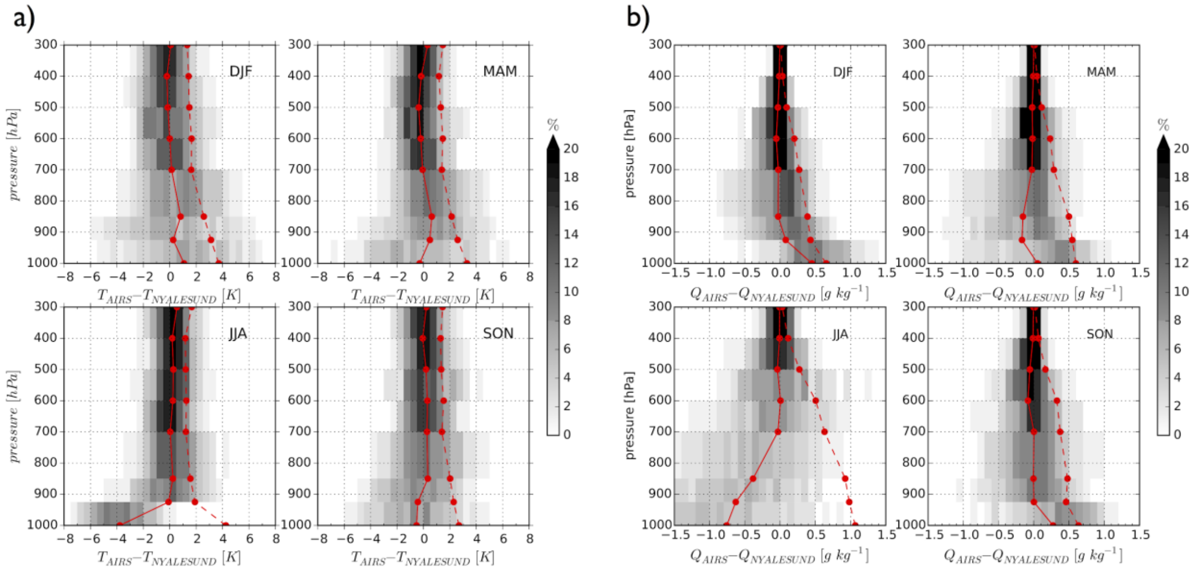

Figure A2. Same as in Fig. 6, but for Ny-Ålesund, Svalbard.

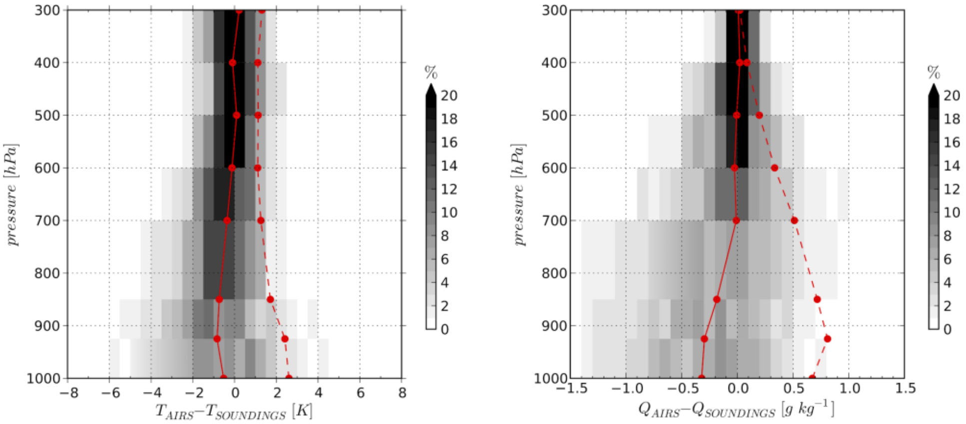

Figure A3. Same as in Fig. 6, but for all central Arctic field campaign profiles combined. Seasonal distributions are not shown because the majority of field campaign observations operated during summer and autumn.

A2.3.3. Large scale atmospheric flow impact on AIRS thermodynamic biases

In this section, seasonal biases in AIRS thermodynamics relative to radiosoundings at Barrow and Tiksi are analyzed with respect to predominant wind direction. Daily averaged atmospheric wind direction at the 700 hPa was analyzed from ERA-Interim reanalysis over a 2°x2° box around each observatory. Days with a 700 hPa predominant wind direction between X-X sector were sampled as northerly wind days; winds within the sector of X-X were sampled as southerly wind days. T and Q profiles for the northerly and southerly wind days were compiled seasonally and were compared to radiosoundings. These polarizing wind sectors were chosen to examine the impact of off-ice flow (northerly winds) versus off-land flow (southerly winds) on T and Q. For comprision, daily-averaged T and Q profiles from the nearest ERA-Interim grid box were also compared to radiosoundings from the Barrow and Tiksi observatories.

The seasonal comparison of error distribution, MBE and RMSE profiles for AIRS and ERA-Interim T relative to radiosoundings sampled for the 2 wind directions are shown in Fig. A4. Compared to AIRS, ERA-Interim MBE and RMSE profiles of T are more similar to the radiosoundings, regardless of northerly or southerly flow; the interquartile and 10th-90th percentile spread in T errors are also more narrow than for AIRS. Looking specifically at predominant wind direction, error distributions, MBE and RMSE are all larger for the southerly, off-land flow regime than they are for the northerly, off-ice (or open water) regime, especially across the lower troposphere. Enhanced daily temperature variability over land compared with that over sea ice appears to signal a flow regime dependence where lower tropospheric temperatures are somewhat constrained by the characteristics of the surface. Averaging of the important diurnal cycle of T over land compared to a less responsive diurnal cycle over sea ice or open water may also be contributing to the enhanced error distributions during southerly flow patterns. Similar to AIRS, ERA-Interim generally has a warm bias in lower tropospheric T during winter, a typical feature found at all observatories analyzed. However, at Tiksi this winter T bias is negative regardless of predominant wind direction (Fig. A4b).

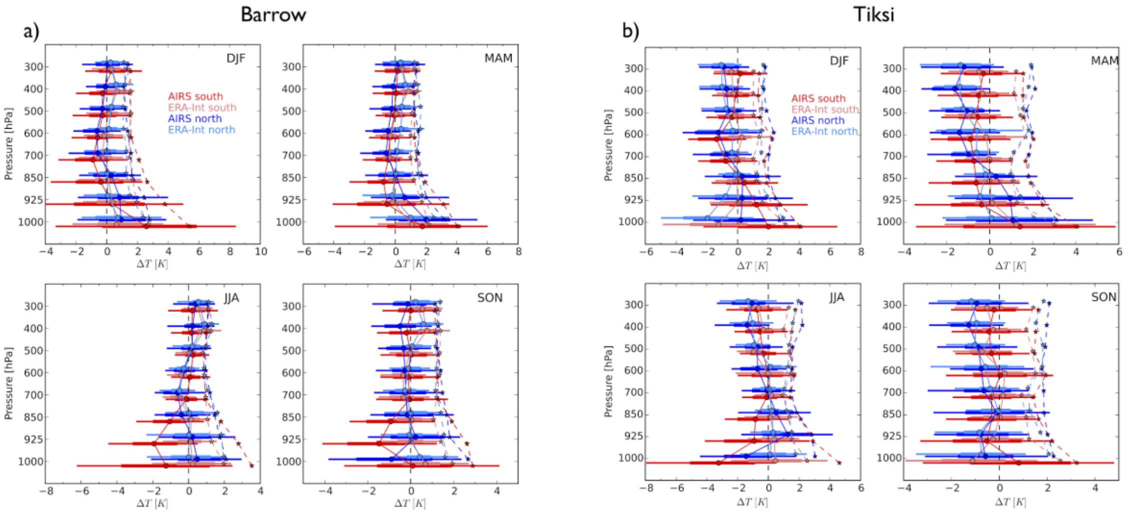

Figure A4. Seasonal T box and whisker error distributions (25-75th and 10-90th percentiles), MBE (solid lines) and RMSE (dashed lines) relative to radiosoundings at a) Barrow and b) Tiksi. Distribution and error statistics profiles for southerly flow for AIRS (red) and ERA-Interim (light red), and northerly flow for AIRS (blue) and ERA-Interim (light blue).

Consistent with results shown in Sec. 2.3, AIRS Q profiles are distinctly drier across much of the lower troposphere, and this dry bias is larger during southerly flow regimes than for northerly regimes (Fig. A5). While ERA-Interim also contains a dry bias at Tiksi (Fig. A5b), the MBE is very close to 0 g kg^{-1} at Barrow (Fig. A5a). Similar to the T distributions, the error distributions in Q are largest during southerly flow, generally resulting in larger RMSE for southerly flow compared to northerly flow. This suggests that the lower tropospheric water vapor variability is more constrained through air mass modification processes occurring over the sea ice as it is advected from the north.

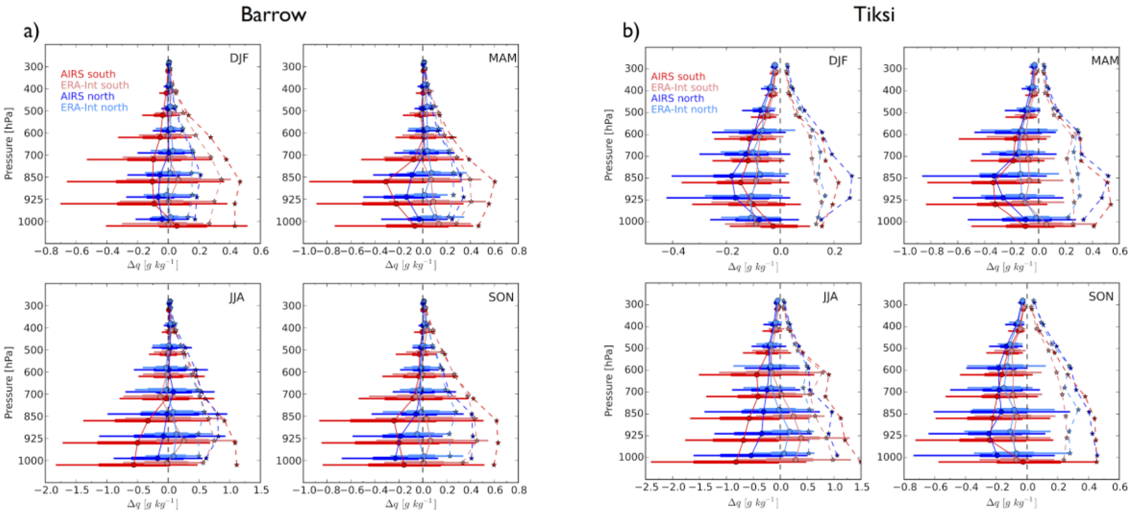

Figure A5. Same as in Fig. A4, but for Q.

A2.3.4. Lower tropospheric process relationships in AIRS and radiosoundings

Temperature structure in the lower troposphere is important for characterizing atmospheric stability, and here the impact of limited vertical resolution of AIRS on stability structure is examined. The seasonal relationship between daily-averaged AIRS and radiosounding temperature differences between 925 and 1000 hPa levels are examined in Fig. A6. The Barrow, Tiksi and combined field campaign temperature structure are, in general, the most consistent among the seasons. During winter and spring, the dominant peak in the distributions indicate a frequently observed stable lower troposphere, with agreement between AIRS and radiosounding profiles; at Tiksi, there is a less dominant increase in lower tropospheric temperatures, which is well captured by AIRS (r=0.72). The winter and spring temperature differences at Ny-Ålesund are distinctly different from Barrow and Tiksi, although AIRS and radiosoundings both reflect this difference. For these seasons, temperatures are frequently decreasing, but AIRS tends to underestimate these decreases with respect to radiosoundings, resulting in low correlations (r=0.08-0.2).

In summer, the spread between positive and negative temperature differences is largest at Barrow, although AIRS and soundings are in agreement here (r=0.73). But for the other observatories, the RFDs indicate the negative temperature differences between 925 and 1000 hPa are more frequent; AIRS generally underestimates the magnitude relative to soundings, which show peak values near -5 K, a value close to the moist adiabatic lapse rate. By autumn, negative temperature differences are most frequently observed by both AIRS and radiosoundings, but again AIRS temperature differences are underestimated. Underestimation by AIRS may be related to retrieval errors within frequent fields of view that are contaminated by low-level clouds, which are ubiquitous during the Arctic summer and and autumn seasons (e.g., Wang and Key, 2005; Shupe, 2011). The RFD of low-level temperature differences for all field campaigns generally indicates a good agreement between AIRS and radiosoundings (r=0.66).

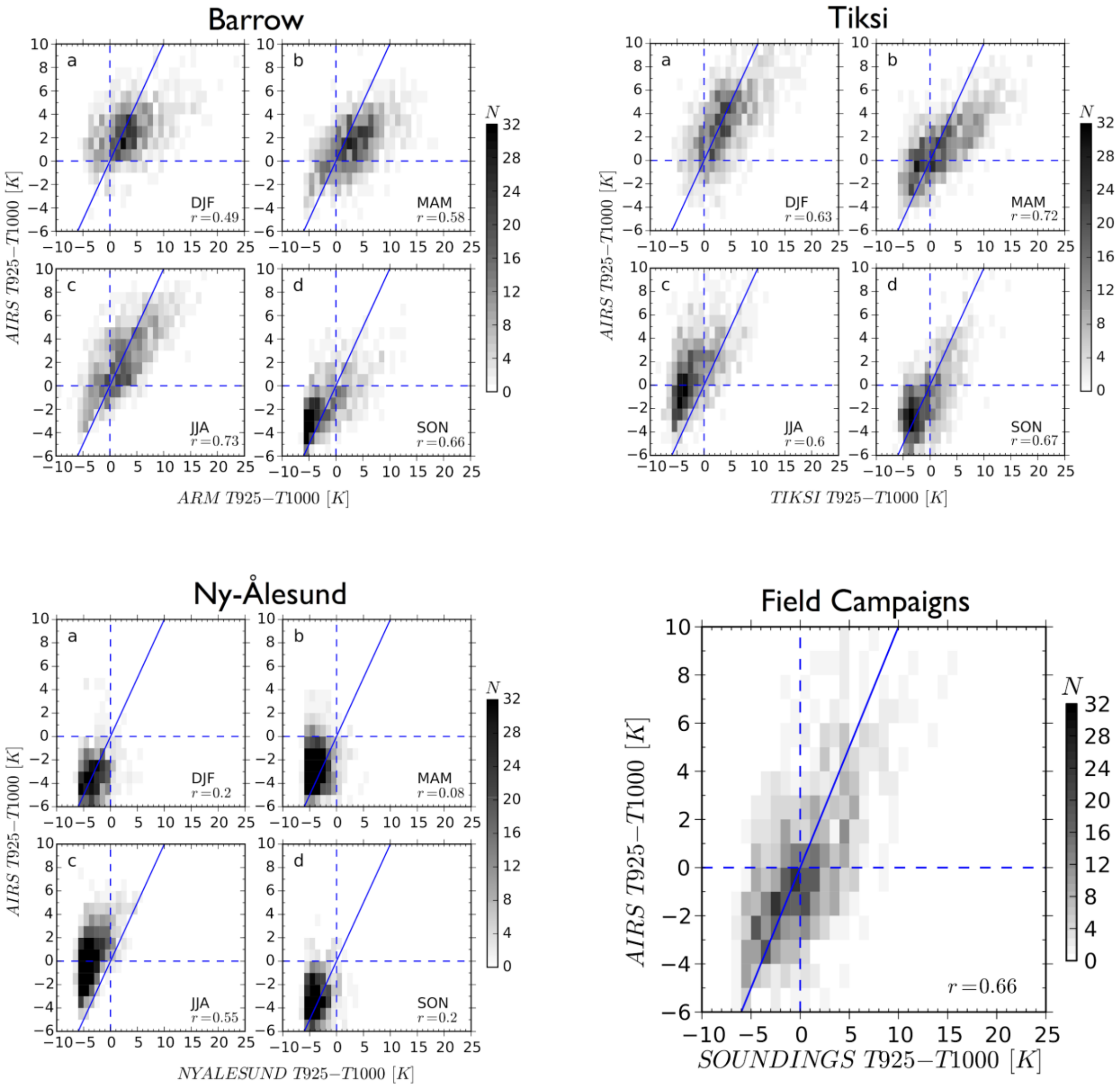

Figure A6. RFDs [counts] of binned temperature differences [K] between 925 and 1000 hPa from daily-averaged AIRS versus radiosounding profiles at Barrow (upper left), Tiksi (upper right), Ny-Ålesund (lower left) and combined field campaigns (lower right). The 1:1 line is shown as solid blue, and the correlation coefficients are included in the bottom right corner of each panel.

The relationship between Q and T across the lower troposphere for AIRS and radiosoundings are examined next. Figure A7 shows the scatterplot difference in Q against the difference in T between the 850 and 925 hPa pressure levels. The median relationship (solid lines) between Q and T differences are relatively similar for AIRS and soundings for all seasons and at all locations. This indicates that AIRS has the capacity to observe thermodynamic features within the lower troposphere associated with horizontal transport processes. The figure does reveal that AIRS is considerably under-dispersive in the daily mean relationship between T and Q relative to radiosoundings.

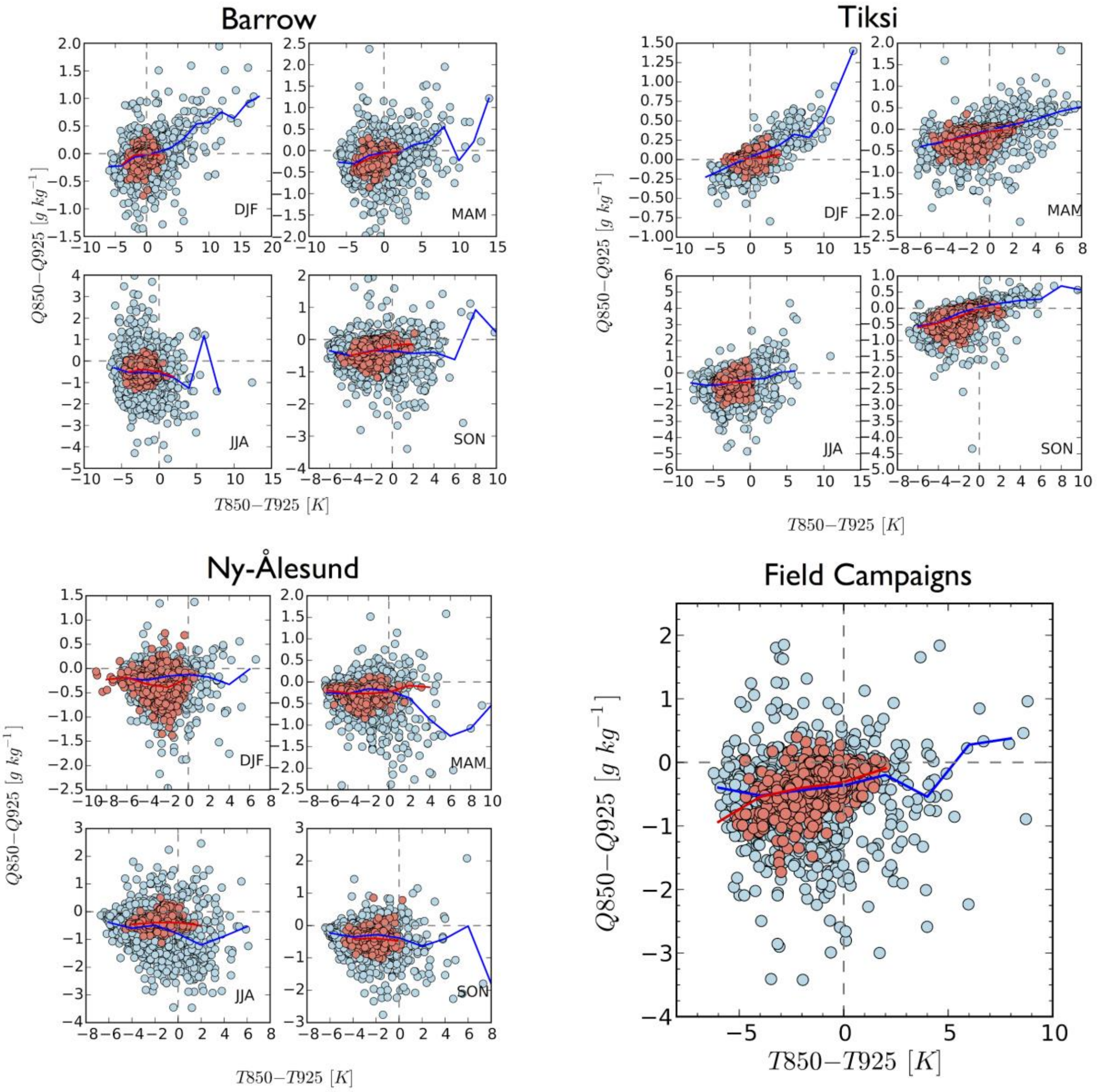

Figure A7. Seasonal scatter plot relationship of daily 850-925 hPa Q differences [g kg-1] versus 850-925 hPa T [K] differences for AIRS (red circles) and radisoundings (blue circles). The median Q differences as a function of binned T differences are shown in solid red (AIRS) and blue (radiosounding) lines.

A2.3.5. AIRS thermodynamic error characteristics under atmospheric radiative states Large scale atmospheric flow impact on AIRS thermodynamic biases

Considering the relatively large error distribution, MBE and RMSE in AIRS lower tropospheric thermodynamics, here an attempt to identify the influence of clouds on the T and Q retrievals from Barrow is performed. Stramler et al. (2011) found that the net surface longwave radiation as an important metric to determine the radiative state of the atmosphere. Since clouds greatly enhance the absorption and reemission of longwave radiation to the surface, the net longwave flux can be used to identify radiatively opaque (cloudy sky) and radiative clear (clear sky or radiatively) atmospheric states. Classifying the atmosphere into these radiative have since been used to examine process-level relationships related to clouds and radiation, and air mass transformations (e.g., Morrison et al., 2012; Engström et al., 2014; Pithan et al., 2014; Persson et al., 2017).

A seasonal RFD of daily net longwave (LWN) surface radiation from Barrow is shown in Fig. A8. During winter at SHEBA, Stramler et al. (2011) found a distinct bimodal distribution in surface LWN, which made it convenient to separate the atmospheric states radiatively as clear (LWN < -30 W m^{-2}) and opaque (LWN > 10 W m^{-2}). The distributions at Barrow do not have the same bimodal distribution (Fig. A2.4.8). Here, a separation is made at LWN < 30 W m^{-2} for the radiatively clear state, and at 20 W m^{-2} for the radiatively opaque state; for SON, the thresholds are shifted to -25 and -15 W m^{-2}, respectively.

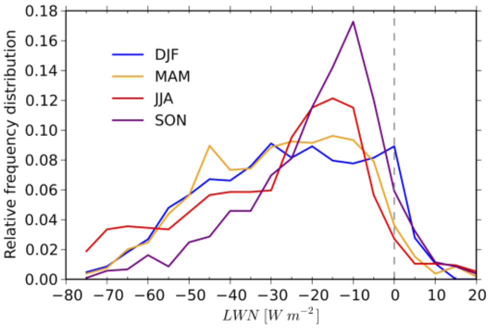

Figure A8. Seasonal LWN frequency distributions at Barrow, Alaska.

AIRS relative to radiosounding T and Q error distributions and statistics separated for radiatively clear (effective clear sky) and radiatively opaque (cloudy sky) atmospheric states are presented in Fig. A9. For both T and Q, the spread in the vertical error distributions is larger for the radiatively opaque state compared to radiatively clear state. This increased error distribution is primarily present from near the surface up to ~600 hPa. Across this lower to mid-tropospheric layer, the RMSEs for the radiatively clear state also decrease more rapidly with increasing height compared to the radiatively opaque state, especially for the Q profiles. Using the LWN subsamples as a proxy for cloud cover suggests that the presence of clouds are likely impacting the retrieval accuracy of AIRS thermodynamics, especially across the lower troposphere where Arctic cloud fractions are typically large.

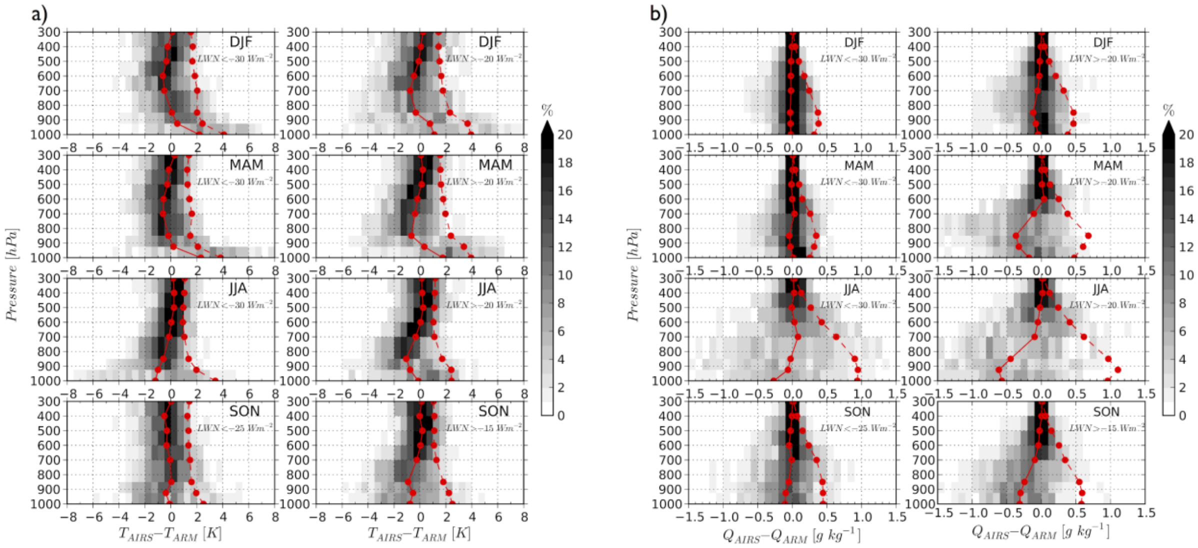

Figure A9. Seasonal a) T [K] and b) Q [g kg^{-1}] error distribution frequency (AIRS minus radiosoundings, contours [%]), MBE (solid red) and RMSE (dashed red). The left-most *columns in a) and b) are the error distributions during the radiatively clear LWN atmospheric state; the right-most columns in a) and b) are for the radiatively opaque LWN atmospheric state (see text).*

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