Integrated Arctic Observation System

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Deliverable 3.9

First implementation and data: Atmosphere and land

Data delivery and results of the distributed systems for atmosphere and land

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EXECUTIVE SUMMARY
This document reports the activities of the **Task 3.5, Deliverable 3.9** ***"First implementation of the observing system: data delivery and report on results of the distributed observing systems for atmosphere and land*"**. D3.9 focuses on (a) atmospheric observation of the main greenhouse gases (CO_2 and CH_4) using ground, mobile and airborne eddy covariance observations to determine the atmospheric concentrations and fluxes in North slope of Alaska and Sweden; (b) trace gases monitoring of N_2O, SF6, CO, O_2/N_2 using a flask sampler for the automated collection of air samples under standardized conditions; (c) effects of snow cover on surface energy balance and permafrost thermal regime; (d) observation with a spectro -albedometer at high temporal resolution, and VNA-based radar system to monitor soil, snow and surface vegetation properties; (e) multiple airborne campaigns conducted in the Alaskan North Slope, Mackenzie River Delta, Canada, and the Lena River Delta, Siberia, assessing the composition and height of the atmospheric boundary layer as well as greenhouse gas concentrations; (e) development of a low-maintenance atmospheric observatory onboard of the Swedish research icebreaker Oden that include measurements of incoming broad-band radiation, surface temperature, cloud-base lidars and eddy covariance fluxes of CO_2 and CH_4 Referenced materials and products in this report were compiled with inputs from the INTAROS partners of the Task 3.5

Table of Contents

1. Introduction

The activities of the Task 3.5 focused on demonstrating the opportunities that arise from the use of new technology to fill spatial, temporal, and methodological gaps in existing atmospheric and terrestrial networks across the arctic. This task is designed to enhance the monitoring of atmospheric composition by experimental observations of greenhouse gas (GHG) CO_2 - CH_4 fluxes and concentrations, trace gases signals of N_2O, SF6, CO, O_2/N_2 and isotopes (e.g. 13C-CO_2, 13C-CH_4, 2H-CH_4, 18O) as well as improve spatial and temporal coverage of GHG fluxes in the arctic Regions in the attempt to provide continuous, year-round data. The task also (a) quantified the effects of snow on surface energy balance and permafrost thermal regime through the deployment of novel technology to monitor snow thermal conductivity at several heights in the snowpack, (b) installed a spectro-albedometer covering the full solar range (350-2500 nm) at high temporal resolution, and a VNA-based radar system to monitor soil, snow and surface vegetation properties, (c) improved the spatiotemporal coverage of atmospheric observations in the central Arctic, through the development of a semi-autonomous observations on the Swedish research icebreaker Oden, and the deployment of a stable isotope measurement infrastructure on ships in the marginal ice zone north of Svalbard. Multiple airborne campaigns were conducted during the period 2012-2019 covering several arctic regions in the attempt to assess the composition and height of the atmospheric boundary layer and the greenhouse gas fluxes observation at regional level.

2. First implementation and operational use of the distributed observing systems for atmosphere and land

The partners of the Task 3.5 provided an overarching scheme of the main results, obtained so far, that mirrored the task description of the grant agreement. The MPG successfully installed a flask sampler for the automated collection of air samples under standardized conditions: due to a series of logistic problems the flask sampler was not installed at the planned site (Ambarchik Northeast Siberia) but in a station in North of Greenland has been chosen as temporary deployment site for the period summer 2019 to summer 2020. The first set of flask is scheduled to be processed in laboratory in early 2020. The USFD and UNEXE successfully managed the maintenance of the five eddy covariance (EC) towers located in North Slope of Alaska: data collected were used to provide the CH_4 emission at the sites investigated, and compare the emission measured with airborne observation. In order to increase the data coverage of the EC tower throughout the year two new sonic anemometer, both equipped with an internal heating system were installed and the data are currently under analysis. CNRS-Takuvik monitored a series of climate-relevant variables in the atmosphere, snow and soil in a series of sites located in Northern Quebec. Main Objective of the observation was investigate the warming-induced effect on vegetation growth, snow properties and permafrost thermal regime.

The FMI successfully installed a spectro-albedometer in March 2019, at the FMI observational premises in Sodankylä, Finnish Lapland, able to measures surface albedo spectra in the 350-2500 nm wavelength range at 3-10 nm resolution every 2 minutes. Data collection include counts of photon upward and downward, spectrum of incoming and reflected irradiance, spectrum of surface albedo. Moreover a SodScat radar and Elbara-II and SodRad radiometer systems were installed in the summer of 2018 on a new observation tower at the FMI-ARC: these radiometer will provide continuous measurements of the active and passive microwave response of the boreal forest landscape in controlled condition. The GFZ used two different airborne platforms the research aircraft *Polar 5* and the helicopter towed *Helipod* for a series of airborne observations of the atmospheric boundary layer composition and greenhouse gas concentrations along different route in north slope of Alaska, Canada and Siberia. The MISU successfully completed the installation of instruments to measure the incoming broad-band radiation, surface temperature, and visibility and cloud-base lidars onboard of the Swedish research icebreaker Oden as well as continuous observation of CO2 and CH4 fluxes using the eddy covariance technique.

2.1. MPG

Contributors: Mathias Göckede, Martijn Pallandt.

2.1.1. Results of the first operational implementation

MPG started working with a flask sampler that can be used for the automated collection of air samples under standardized conditions. The sampler can be operated to fill one, two or three liter Normag flasks (NORMAG Labor- und Prozesstechnik GmbH) with gear-wheel connection. A full sized sampler (see e.g. Figure 1, left panel) consists of five drawers. Each of the upper four drawers hosts ports for up to 6 glass flasks, while the lower drawer contains the control electronics and all necessary components for the sampling procedure. The sampler version used by MPG is a smaller version compared to the one shown on the left of Figure 1, consisting of just 3 drawers, therefore capable of holding up to 12 flasks at a time. The integrated software allows for a detailed monitoring of flow processes and flask status. The right panel of Figure 1 shows an example of the flow scheme monitoring tool, indicating the states of all integrated valves, pumps, flask ports, sensors and mass flow controllers. Similar tools exist for the monitoring of flask status, or the generation of sampling schedules and/or event triggered sampling modes.

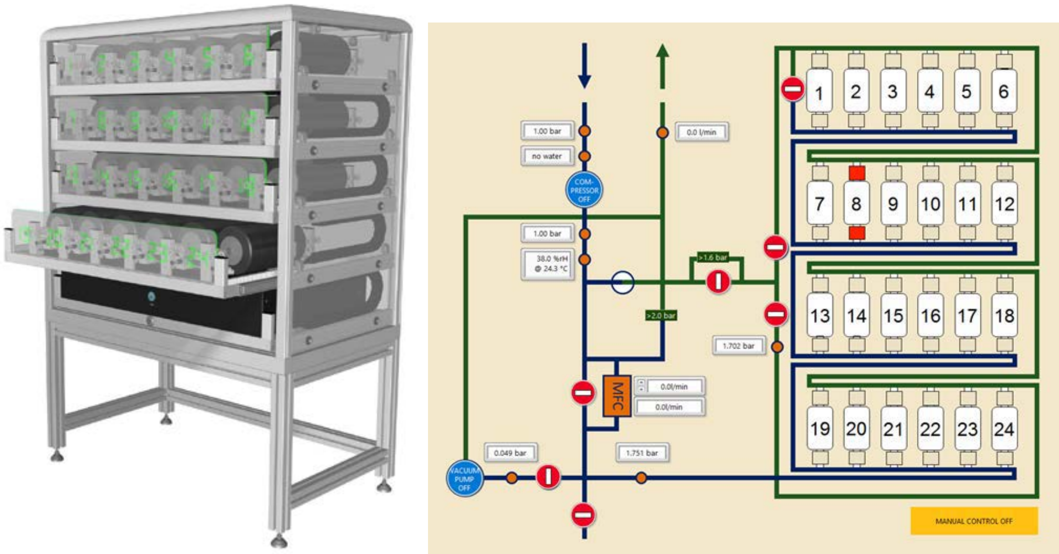

Figure 1. (left) Front view of a 24 port flask sampler. (right) control panel showing the flow scheme within a 24-port sampler.

Samples can be filled according to a fixed, user-prescribed schedule, based on external triggers, or manually triggered. The flow scheme design allows for the simultaneous filling of multiple flasks, which would in this case receive exactly the same input flow. Also the duration of the filling time and the filling method (e.g. air exchange vs. time-integrated) can be modified.

Installation of the instrument was originally planned for the site Ambarchik in Northeast Siberia (see also Figure 2). At that site, MPG has been operating an atmospheric observatory since summer 2014 that continuously monitors the atmospheric trace gases CO_2, CH_4 and H_2O. After completion of instrument construction in January 2019, and finalizing the recommended quality assessment procedures in March 2019, the shipment to Russia that was intended to leave Germany in April 2019 encountered unexpected problems with customs procedures for the import of the flask sampler. The resulting delays lasted into summer 2019, jeopardizing the successful installation of this instrument in the Arctic for which, due to weather and transport conditions, only a narrow time window in July and August is available. In order to facilitate the timely installation, and the commencement of the data acquisition, we therefore decided to develop an alternative deployment strategy.

We selected Station North on Greenland (see also Figure 2) as a temporary deployment site for the period summer 2019 to summer 2020. This site, also called Villum Research Station (http://villumresearchstation.dk) is a research facility at a military outpost in high arctic North Greenland (81°36’ N, 16°40’ W). It is owned by the Greenland Government and is being operated by Aarhus University (Denmark) in cooperation with the Danish Defense (the Arctic Command). Colleagues from Aarhus University are currently in the process of upgrading the facilities to fulfill the requirements for a monitoring site of the European ICOS observation network. The MPG flask sampler has been integrated into this concept, and will at least temporarily supplement the continuous greenhouse gas measurements.

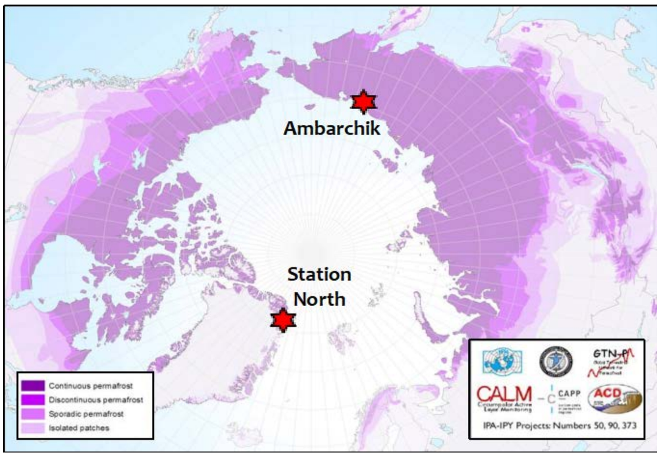

Figure 2. Locations of flask sampler deployment. See main text for more details.

Field work for the installation of the flask sampler took place in late August to early September 2019. The field crew successfully managed to set up air inlets for an intake height of 50m a.g.l., and connect the sampler to the existing meteorological monitoring system to facilitate sampling triggered by external conditions. Since early September 2019, the sampler has been operating smoothly, and collects air samples according to the schedule and conditions defined by MPG (see also details below).

2.1.2. Description of provided data

The datasets collected by the automated flask sampler are supposed to improve our ability to constrain atmospheric transport and surface-atmosphere exchange processes in the Arctic. With the shift in deployment location from Ambarchik to Station North, the immediate focus area, i.e. the Arctic region that dominates the signals collected in the flasks, has shifted from East Siberia and the adjacent shelf areas of the Arctic Ocean to Greenland, the North Canadian archipelago and the Norwegian and Beaufort Seas.

The currently implemented sampling scheme uses up the 12 flasks that can be mounted in the sampler at one time within a period of 5 weeks. Once per week, a single sample will be taken at a fixed schedule. In addition, 5 more flasks will be filled based on the prevailing transport situation. In this mode, the system checks the characteristics of the incoming winds at Station North, and, given that the transport conditions are stable enough over time, fills separate flasks for 5 different source domains surrounding the site. Two additional flasks are reserved to sample air with exceptionally high CO_2 and CH_4, respectively, mixing ratios, with the intention to better constrain the sources of high greenhouse gas emission events in the Arctic target domain. The sampling schemes are customized based on the availability of flasks, and the schedule for flask logistics that can be provided by the Danish military. Accordingly, more frequent sampling could potentially be made possible in the upcoming months, provided that MPG will get sufficient space on supply flights to Station North.

With the operation of the flask sampler just started in September 2019, at the time of writing no samples could be retrieved from the station, and accordingly no new datasets have been produced yet. The first set of flasks that is currently in use is expected to be replaced in early December 2019, so assuming that the shipment back to Germany goes according to plan, a processing of the samples in the laboratory in Jena, Germany, can be scheduled for early 2020.

2.1.3. Plans for the final implementation

As briefly mentioned above, the flask sampler deployment on Station North is currently regarded as a preliminary solution. It allows us to collect highly relevant data from a sensitive Arctic region, and fill a crucial gap in the previously existing Arctic atmospheric monitoring network. Still, our main target is a deployment of the instrument at the Ambarchik site, where we plan to produce new datasets that will particularly help constraining greenhouse gas emission sources from the East Siberian Arctic Shelf region. We will use the coming winter to solve outstanding problems regarding to shipment and import of this instrument into Russia, with the aim of facilitating a smooth shipment to Siberia in early summer 2020. In case the customs problems encountered earlier in 2019 persist, we will continue the operation of the instrument at Station North for the 2nd field season.

2.2. GFZ

Contributors: Torsten Sachs, Katrin Kohnert.

2.2.1. Results of the first operational implementation

Aircraft-derived vertical atmospheric profiles are campaign-based by nature and in our case project-/proposal-based and thus not an operational system in the sense of continuous or regular observations. The contributed data are from past campaigns and described below. The system set-up has been described in detail in Deliverable 3.5.

2.2.2. Description of provided data

We have conducted multiple airborne campaigns in the period 2012-2019 covering the Alaskan North Slope, the Mackenzie River Delta, Canada, and the Lena River Delta, Siberia. Scalar mixing ratios and temperature profiles have been (re-)processed consistently for most of the 2012-2016 campaigns. The campaigns were based out of Utqiaġvik (formerly Barrow) for growing season coverage of the Alaskan North Slope in 2012, 2013, and 2016; Inuvik for coverage of the Mackenzie River Delta and adjacent coastal plains in 2012, 2013, and 2016; and out of the Research Station Samoylov Island for coverage of the Lena River Delta in August 2012 as well as April, June, and August 2014.

In all three study areas, the campaigns aimed at conducting greenhouse gas flux measurements (see INTAROS reports D2.7 and D2.8) while also assessing the composition and height of the atmospheric boundary layer (see also INTAROS report D2.4). Flights consisted of horizontal flight tracks in about 40 m – 80 m above ground level for greenhouse gas flux measurements and vertical profile flights within and above the atmospheric boundary layer at the beginning and the end of each flight track ranging from several hundred meters altitude to >2000 m altitude (Figure 3).

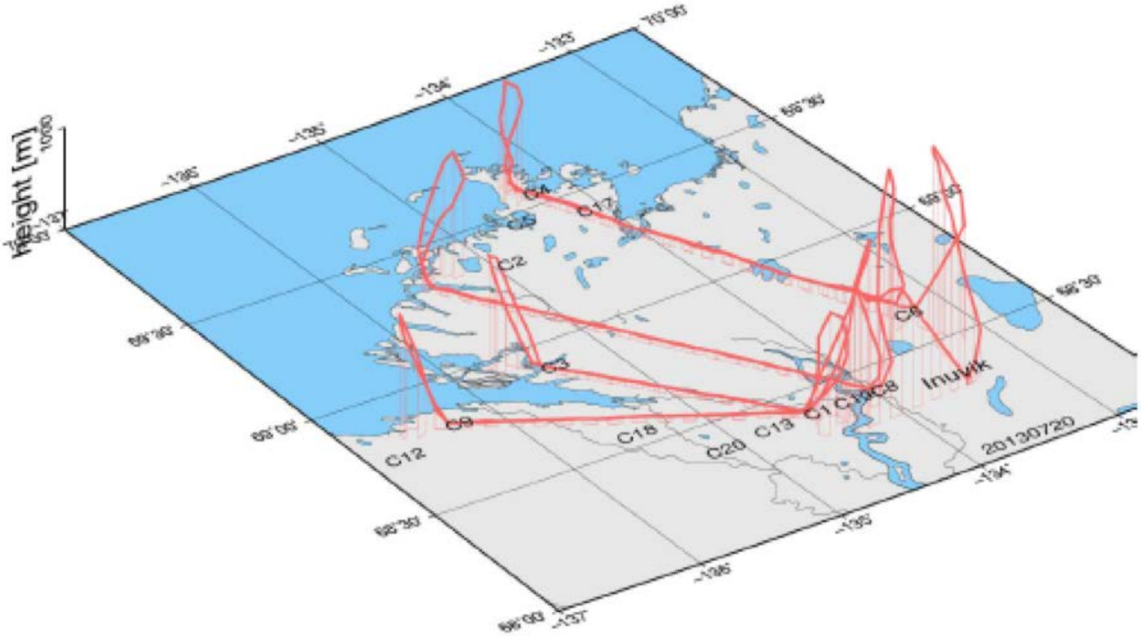

Figure 3. Exemplary flight pattern across the Mackenzie Delta including horizontal flight tracks close to the surface and vertical profile flights. Figure by Jörg Hartmann.

We used two different airborne platforms: the research aircraft *Polar 5* owned by the Alfred Wegener Institute - Helmholtz Centre for Polar and Marine Research (AWI) for campaigns in Alaska and Canada and the helicopter-towed *Helipod* provided by Technische Universität Braunschweig in Siberia. Aboard *Polar 5*, greenhouse gas concentrations were measured in sample air drawn from an inlet tube at the top of 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.) from 2013 onwards (CH_4, CO_2 and water vapour). Air temperature was measured with an open wire Pt100 in an unheated Rosemount housing.

Helipod was equipped with an open path CH_4 sensor Li-7700 (Licor) and an open path CO_2 and H_2O sensor Li-7500 (Licor). Air temperature was measured with a Pt100 by Rosemount and a fine wire by Dantec, and air humidity by Lyman Alpha sensor L6 (Buck Research).

Hundreds of individual vertical profiles were extracted from the continuous data sets of 2012 and 2013 and stored in 1 Hz temporal resolution with a UTC time stamp. Position data are provided in decimal degrees, the altitude is given as GPS altitude and needs to be converted to altitude above ground level if of interest for the user. In addition to atmospheric pressure (in hPa), air temperature (in °C) and the 3d wind vector (in m s^{-1}), CH_4 concentrations are currently available in wet mole fractions and H_2O concentrations in dry mass fractions.

Processing later years has been delayed by the early departure of the responsible project scientist and difficulties in finding an adequate replacement.

2.2.3. Plans for the final implementation

No new measurements were proposed or foreseen during INTAROS and neither aircraft nor Helipod are available in 2020 due to their deployment in the MOSAiC Expedition. Depending on funding, data from future flights and/or other platforms (such as UAS systems) benefit from an established workflow that allows quick extraction and visualization of atmospheric profile data.

2.3. UNEXE

Contributors: Terenzio Zenone, Walter Oechel.

2.3.1. Results of the first operational implementation

The UNEXE provided the first annual balance of both CH_4 and CO_2 fluxes in a total of five sites spanning a 300Km transect across the North Slope of Alaska as well as an estimation of the regional CH_4 emissions based on aircraft observations. Ecosystem scale of CO_2 and CH_4 fluxes were measured using the eddy covariance (EC) method with three (CMDL, BES, BEO) EC towers in Barrow (71.3225269N, 156.6091798W, one in Atqasuk (ATQ, 70.4696228N, 157.4089471W), and one in Ivotuk (IVO, 68.48649N, 155.75022N). The EC towers in CMDL, BEO, and BES, and ATQ are all equipped with a closed-path LGR analyzer (FGGA, Los Gatos Research, Mountain View, CA, USA), for the monitoring of CO_2 and CH_4 while the most remote site IVO is equipped with LI- 7700 and LI 7200 for the monitoring of CH_4 and CO_2 respectively. A wide range of meteorological variables are measured at each of the five EC towers including: photosynthetic active radiation, net radiation, incoming solar radiation air temperature, relative humidity, soil heat flux, snow depth as wells as soil temperatures and soil moisture measured in several location and depth at each site in order to represent the spatial and vertical variability. These observations allows to report the year-round CH_4 emissions: we find that emissions during the cold season (September to May) account for ≥50% of the annual CH_4 flux, a notably higher contribution than previously modelled, and also higher than observed in boreal Alaska regions, with the highest emissions from non inundated upland tundra. Cumulative emissions for the cold season averaged 1.7 ± 0.2 [mean ± confidence interval (CI)] g C-CH_4 m^{-2} at our five sites, accounting on average for 50 ± 9% (mean ± CI) of the annual budget.

We also investigated the CO_2 and CH_4 soil diffusivity, at BES site in Barrow (See Figure 4) in the attempt to discern if they have been stored or actively produced in the soil column: continuous measurements of CO_2 and CH_4 concentrations were made along a soil profile (e.g. -10, -20, -30 cm depth) using a cavity ring- down spectroscopy gas analyzer (CRDS) and hydrophobic tube membrane in closed loops to the CRDS: while the data collected indicate that biological activity beneath the upper freezing soil surface occurs during the fall shoulder season a detailed understanding of the interaction and gas exchange cannot yet be well determined.

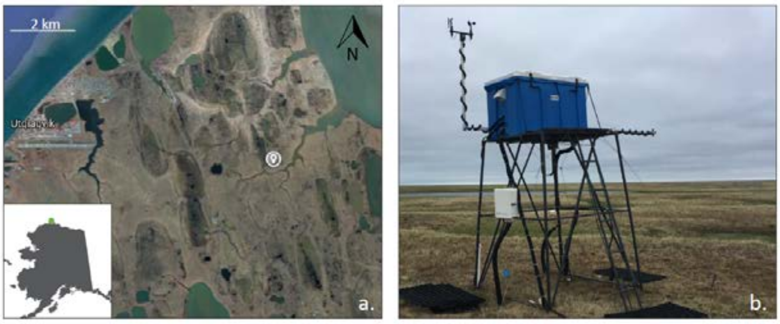

Figure 4. (a) Location of the study relative to Barrow (AK); (B) Sub-surface CO_2 and CH_4 monitoring system with associated metereological measurements.

Regional fluxes of CH_4 were estimated from analysis of 15 aircraft flights over the North Slope, part of National Aeronautics and Space Administration's Carbon in Arctic Vulnerability Experiment (CARVE). Regional CH_4 fluxes calculated from aircraft observations show a strikingly consistent pattern to our eddy flux data, notably including the persistence of CH_4 emissions into the cold season. Scaled to the circumpolar Arctic, cold season fluxes from tundra total 12 ± 5 (95% confidence interval) Tg CH_4 y^{-1}, ~25% of global emissions from extratropical wetlands, or ~6% of total global wetland methane emissions. The dominance of late-season emissions, sensitivity to soil environmental conditions, and importance of dry tundra are not currently simulated in most global climate models.

2.3.2. Description of provided data

This data available include year-round measurements CH_4 and CO_2 flux along with the series of environmental variable (describe in the section 2.3.1) at the five EC towers at sites. The included site-level flux data at half-hourly intervals were calculated following standard eddy covariance data processing procedures Data are available at:
https://catalog-intaros.nersc.no/dataset/doi-10-18739-a2tm72117.

Airborne CH_4 and ozone (O_3) measurements collected during Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE) are available at:
https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1300.

The reported CARVE airborne CH_4 and O_3 data were aggregated horizontally at 5 km intervals. Measurement heights are reported. A gridded footprints is provided as net CDF formatted files.

2.3.3. Plans for the final implementation

We will continue the observation of CO_2 and CH_4 from the five EC tower in north slope of Alaska also in the attempt to improve the data coverage during the cold season and increasing knowledge of the controls on the interannual variations of the CO_2 and CH_4 fluxes over the entire years and the spatial representativeness of the eddy covariance towers at larger scale: the latter will allow to improve the model simulation for CH_4 emission within an EC domain by considering the effects of soil hydrology and landscape types.

2.4. USFD

Contributors: Donatella Zona

2.4.1. Results of the first operational implementation

Improving year-round data coverage for CO_2 and CH_4 fluxes in the arctic represent a critical challenge due to the extreme weather conditions. In order to tackle these issues and provide year around data coverage we built a defrost system for the sonic anemometer (CSI_CSAT3B) that anyway presented considerable data loss. To overcome such problem two new sonic anemometers (CSI CSAT 3BH) equipped with an embedded heating system were installed in two of our Alaska EC sites (BES and BEO) during the 2019 summer season. (Fig. 5).

Figure 5. New heated sonic anemometer installed in Barrow Alaska during summer 2019.

The CSAT3BH and heater controller box use a heater algorithm to variably control the heaters on the sonic head: heater voltage maintain the temperature on the transducers above dew point when the ambient temperature is less than 2 ^oC. and clear blockage (presumably from ice/snow) based on sonic diagnostic flags. A preliminary comparison between the CSI_CSAT3B and CSI_CSAT3BH showed promising results as indicated by the good agreement between the sonic temperature, and flux of sensible heat measured in both sites. (Fig. 6).

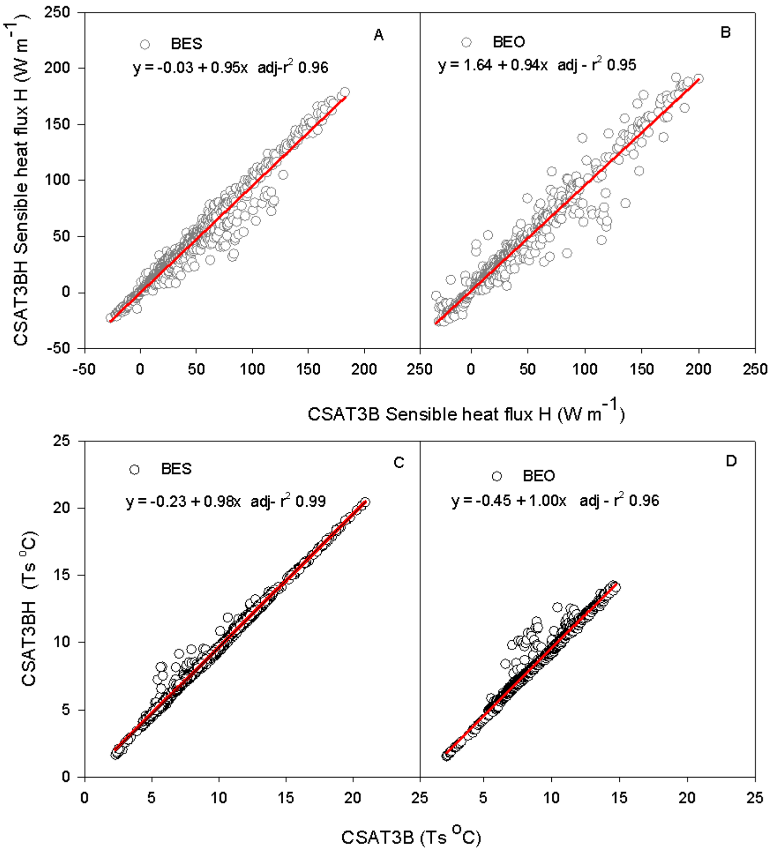

Figure 6. Comparison between CSI CSAT3B and CSI_CSAT3BH measurements of Sensible heat flux at BES and BEO (panel A -B respectively) and sonic temperature panel C and D.

2.4.2. Description of provided data

The University of Sheffield (USFD), the University of Exeter (UEXE) and the San Diego State University (SDSU) are collaborating on data collection, processing, quality control and harmonization of greenhouse gas measurements of the five EC towers, as well as meteorological observations in the surrounding area. As part of INTAROS USFD has been in charge of greenhouse gas measurements and their publication in an open data repository available here:

https://catalog-intaros.nersc.no/dataset/doi-10-18739-a2tm72117.

2.4.3 Plans for the final implementation

While we will continue the observation of CO_2 and CH_4 fluxes from the EC towers in a close collaboration between with SDSU and UNEXE we will evaluate the performance of the two new sonic anemometer installed during winter 2019/2020 and spring 2020: further investigation are needed to identify potential bias on the data recorded when both sonic heaters are ON: in particular identify potential offset between air T and sonic temperature, difference in fluxes of sensible heat derived from the sonic temperature, difference in total wind velocity (U), friction velocity (u*), difference of value and standard deviation of the vertical wind speed (W); the latter are of particularly important because the W fluctuations are required for the determination of any scalar flux by eddy covariance.

2.5. CNRS-Takuvik

Contributors: Florent Domine

2.5.1. Results of the first operational implementation

The objective of CNRS-Takuvik within this WP was to monitor climate-relevant variables in the atmosphere, snow and soil along a latitudinal gradient between 55 and 83°N in Eastern Canada: 2 sites in Northern Quebec (55 and 56°N), one site at Bylot Island (73°N) and one site at Ward Hunt Island (83°N). Besides climate monitoring, the purpose was to gain data allowing process understanding, in particular regarding the impact of warming-induced vegetation growth on snow properties, the permafrost thermal regime, and soil carbon stocks.

2.5.2. Description of provided data

Time series of air temperature, relative humidity, wind speed and radiation are obtained at 4 locations. Furthermore, snow height, thermal conductivity and temperature are monitored at 11 sites at these 4 locations, differing in vegetation type. These variables are monitored at several heights in the snowpack. Soil temperature and volume water content at 5 depths in the active layer are monitored at 16 sites at these 4 locations. Soil thermal conductivity is monitored at 6 sites at our 4 locations. CO_2 fluxes are monitored at one site in Northern Quebec using eddy covariance. Soil carbon stocks have been quantified at 3 of our 4 locations, for different vegetation covers.

2.5.3. Plans for the final implementation

These monitoring activities will be maintained throughout the project and possibly beyond. Data will be archived in the NordicanaD repository. They can be used for forcing and validating land surface models and other models such as snow physics models. The data will be used for process understanding, in particular to investigate the impact of Arctic greening on snow physical properties, the permafrost thermal regime and its carbon stocks.

2.6. FMI

Contributors: Roberta Pirazzini, Juha Lemmetyinen, Anna Kontu.

2.6.1. Results of the first operational implementation

Testing of the SVC-FMI spectro-albedometer in Sodankylä, Finnish Lapland

The SVC-FMI spectro-albedometer was installed in March 2019 over a flat, snow-covered wetland site in the FMI observational premises in Sodankylä, Finnish Lapland (Fig. 7). The installation setup was constructed in advance, before the snow accumulation, so that the observed field remained undisturbed during the positioning of the instrument. The instrument measures surface albedo spectra in the 350-2500 nm wavelength range at 3-10 nm resolution every 2 minutes. To fully test the instrument and exploit the measured spectra, a field campaign was carried out from 18 March until 11 April 2019 where other continuously measuring spectro-radiometers were installed in the same field and intensive measurements of snow macro- and micro-physical snow properties were carried out once or twice a day. The analysis of the collected dataset is ongoing.

Figure 7: SVC-FMI spectro-albedometer installed in Sodankylä, Finnish Lapland.

Testing of the SodScat radar in Sodankylä, Finnish Lapland

The SodScat radar and Elbara-II and SodRad radiometer systems were installed in the summer of 2018 on a new observation tower at the FMI-ARC. The installation will provide continuous measurements (several daily observations) of the active and passive microwave response of the boreal forest landscape in controlled conditions. The tower overlooks a boreal forest site dominated by Scots Pine (*pinus sylvestris*) of varying age. Installed at the height of 21 m, the microwave instrumentation provides observations from above the forest canopy, enabling remote sensing studies related to retrieval of surface parameters over forested areas (where the forest canopy poses a challenge) as well as for retrieval of vegetation parameters themselves (forest biomass and height, vegetation optical depth and water content). A second Elbara-II system is installed beneath the canopy, providing a reference for the above-canopy measurements. The tower installation is part of the Integrated Carbon Observing System (ICOS), providing comprehensive measurements of the local CO_2 flux as well as meteorological and ground measurements. This enables cross-cutting studies with observing changes in CO_2 emission by means of proxy parameters derived from microwave remote sensing (e.g. snow cover and soil properties and their relation to the carbon balance).

Figure 8. Installation of microavequiment in ICOS tower at FMI-ARC in Sodankylä, Finland, in the summer of 2018 (left). SodScat radar overlooking the boreal forest test area in the winter of 2018-2019 (right).

Table 1 summarizes the installed microwave instrumentation. All instruments provide frequencies relevant for several existing satellite systems. Note that while the SodRad and SodScat systems are owned by FMI, the Elbara–II radiometers are currently on loan from the European Space Agency (ESA).

Table 1. Microwave instrumentation installed at FMI-ARC ICOS tower.

Instrument name	Type	Frequencies	Owner	Reference Satellite system	Notes
SodScat	Microwave radar	1-10 GHz	FMI	Sentinel-1, RCM, Cosmo-SKYMED, TerraSAR-X /Tandem-X	Azimuth and elevation scan capability (scatterometer mode). SAR imaging capability by displacement rail (5 m aperture).
SodRad	Microwave radiometer	10.65, 18.7, 21.0, 36.5 GHz	FMI	SSMIS, AMSR2	Dual polarization, azimuth and elevation scan capability.
Elbara-II	Microwave radiometer	1.4 GHz	ESA	SMOS, SMAP	Two systems installed (above and below canopy). Dual polarization, elevation and azimuth scan capability.

The equipment installation ran through several tests in the winter 2018-2019. Due to the complexity of the system, several problem issues with winter durability, RFI (radio frequency interference) and calibration stability were encountered. As a result, several features of the installation had to be modified and improved after the first field season in the summer of 2019.

2.6.2. Description of provided data

SVC-FMI spectro-albedometer in Sodankylä, Finnish Lapland

The raw data collected every 2 minutes include:

- Counts of photons detected by the instrument after receiving the signal from the upward looking integrated sphere - Spectrum of incoming irradiance.
- Counts of photons detected by the instrument after receiving the signal from the downward looking integrated sphere - Spectrum of reflected irradiance.
- Spectrum of surface albedo.
- Ancillary data needed for the calculation of the irradiance from the raw counts of photons (integration time and temperature of each of the three photodiodes, scanning time, number of averaged spectra during the scanning time).

Before each scan, the instrument automatically measures the dark current and subtract it from the photon counts. For a quick check of the data, after each scan the averaged spectra of incident irradiance, reflected irradiance, and albedo are plotted (see Figure 8), and the plots are saved in a dedicated file.

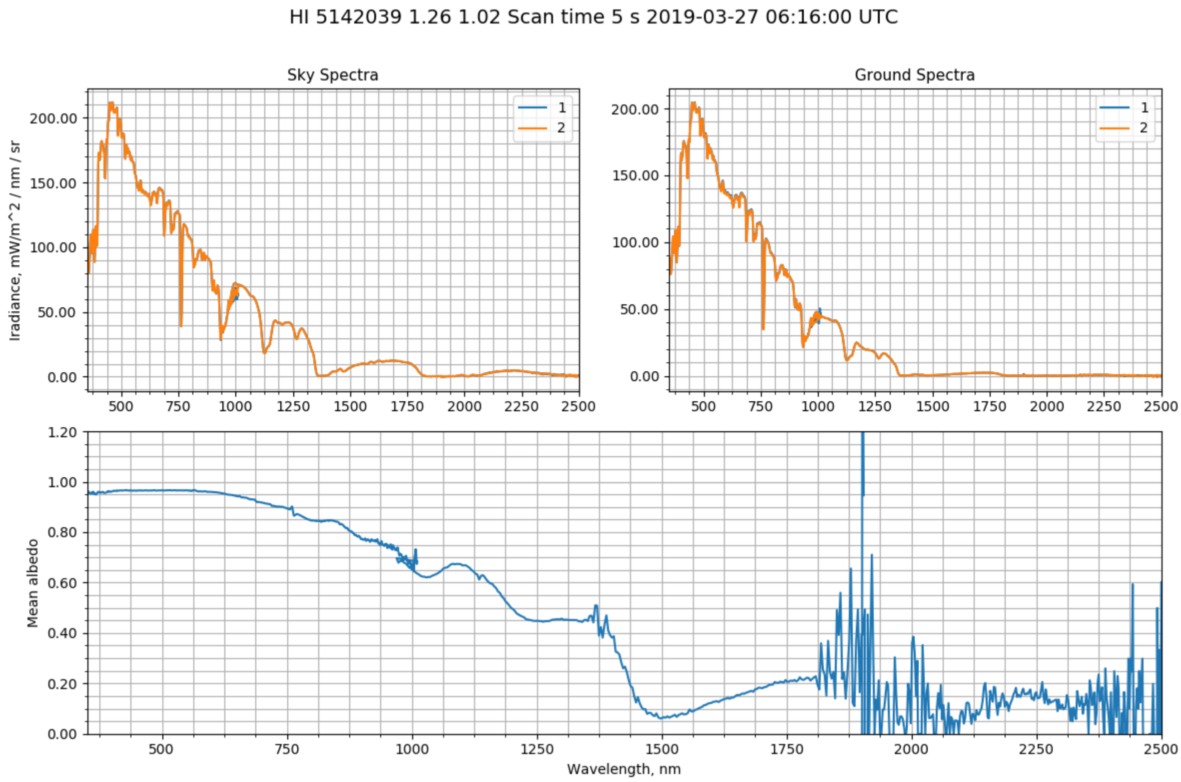

Figure 9: Example of spectra measured by the SVC-FMI spectro-albedometer on the 27 March 2019 at 6:18 UTC.

The figures files, the raw data files, the ancillary data files, and the calculated irradiances and albedo files are stored in a datalogger placed inside the instrument enclosure. Data are then automatically downloaded to the receiving station or laptop via wi-fi connection.

The ongoing data processing after the first campaign includes the development of the routines to correct the data from deviation of perfect cosine response of the integrating spheres, from the thermal drift due to the temperature dependence of the sensor's sensitivity, and from the obstruction of the instrument's field of view caused by the supporting infrastructure. Once the cleaned data are produces and the data processing improved and made semi-automatic, the raw data and the cleaned data will be placed in the data repository of the FMI Arctic Space Center, from where they are openly accessible. The repository is currently under construction to make the data searchable and interoperable.

SodScat radar in Sodankylä, Finnish Lapland

The basic measured L1 variables include:

- Microwave brightness temperature at 1.4, 10.65, 18.7, 21, and 36.5 GHz, H and V polarization. Scan of target area every hour (pause during SAR measurement every 12 hours).
- Microwave backscatter (and phase) at bands of 1-2 GHz, 5-6 GHz, and 9-10 GHz at two polarization configurations (VV, VH). Measurement every 12 hours, 4 hour scan.

The SodRad and Elbara-II radiometer measurements are processed to L1 equivalent, radiometrically calibrated brightness temperatures. Azimuth and elevation information are provided in order to project the measurement on the observation field. Instrument housekeeping information is provided if necessary for verification of thermal stability (essential for retaining correct calibration). The SodScat radar is operated in SAR mode, with SAR image acquisition of the target area occurring every 12 hours. The full observation cycle last 4 hours. During this period, low frequency radiometer measurements are not possible due to RFI contamination; these measurements are thus halted. The data are currently available on demand for scientific use from FMI. Direct dissemination (via web portal etc.) is not encouraged due to complexity of the dataset for the first field season. However, provided continuous operations can be maintained for most of the second filed season, L1 data will be made available through the FMI data portal.

2.6.3. Plans for the final implementation

SVC-FMI spectro-albedometer in Sodankylä, Finnish Lapland

The first measurement campaign in March-April 2019 and the following data processing will hopefully enable the completion of the data management chain needed for operationalization of the SVC-FMI spectro-albedomenter. A second measurement campaign will be carried out in March-April 2020 in the same place, to refine and test the developed procedure. After the first peer reviewed article describing the instrument and measurement routine will be published, the data will be made openly accessible from the FMI Arctic Space Centre.

SodScat radar in Sodankylä, Finnish Lapland

The microwave systems at FMI-ARC are at the moment semi-operational. A goal is to run measurements using a fixed schedule and measurement protocol throughout the second field season. However, research campaigns at the site (also using the same instruments) necessitate occasional measurement periods which deviate from the standard protocol. Also, based on experiences from the first field season, data gaps due to repair, refurbishment and calibration of the instruments can be expected. The second field season will serve as a test bed providing a time series of continuous science observations from the site, helping to further refine measurement protocols and possibly further upgrades to the system.

2.7. MISU

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2.7.1. Results of the first operational implementation

The overarching goal of MISU was to develop a low-maintenance atmospheric observatory for the Swedish research icebreaker Oden. The underlying idea is that with a minimum of berths required for staff, from zero to one (or possibly two), it will be possible to operate this observatory on *all* research missions, regardless of science focus, and thereby enhance the amount of atmospheric data in the central Arctic, especially for vertical structure. The manpower requirements initially come from testing, but over the longer perspective arise from the need – or not - to do radiosoundings with free-flying helium balloons. This is a labor intensive activity and we are currently discussing with the Swedish Polar Research Secretariat (SPRS) for them to take that task over. Most of the instruments were funded by a donation from the Knut and Alice Wallenberg Foundation, and only a smaller portion was funded by INTAROS.

The first deployment of the first phase of instruments was during the Arctic Ocean 2018 (AO2018) expedition, August and September 2018. This consisted of the surface flux installation on the bow mast (Figure 10), an advanced weather station on the 7th top deck, including incoming broad-band radiation, surface temperature, and visibility and cloud-base lidars (Figure 11) and regular 6-hourly radiosoundings from the helideck of Oden (not shown). The soundings were transmitted to the GTS in near-real time. The planned Doppler cloud radar or scanning microwave radiometer were not included at this time, however, AO2018 was an atmospheric research mission and other collaborating groups deployed corresponding instrumentation (see Figure 9). As a part of another collaboration we were also able to measure the eddy-covariance surface fluxes of CO_2 and CH_4.

Figure 10. Photo of the foredeck installations with the foredeck mast with sonic anemometers and gas analyzers for surface flux observations. Also in this photo are the Doppler cloud radar, lidar and the scanning microwave radiometer that was deployed in AO2018 by collaborating groups.

Figure 11. Photos of instruments deployed on the 7th top deck ("monkey island") showing (left) the weather station with the two long- and shortwave broad band radiation sensors in their gimbals, (middle) the present weather/visibility sensor and (right) the ceilometer lidar. All are along the forward railing. Not shown are two infrared thermometers, one on each side looking down at the surface; surface temperature facilitates calculation of upward longwave radiation.

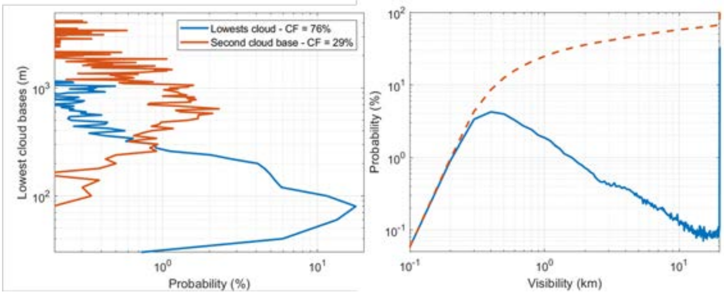

Figure 12. Left, the probability distribution of the lowest cloud base, and in the case with more than one layer also the second lowest cloud base; the average cloud fraction (CF) is also given in the legend

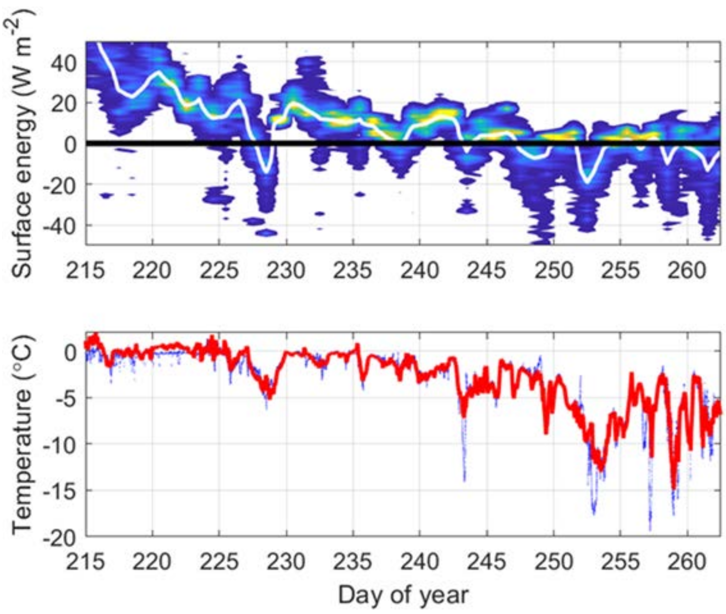

Figure 13. Time series of (top) the pdf of the daily surface energy budget (white line is median), and (bottom) air (red) and surface (blue) temperature. Note the energy budget decline as the sun sets and the temperature drops with temporarily lower energy budget, as low clouds dissipate.

As an example of results, Figure 12 shows statistics of the lowest and second lowest cloud bases from the cloud base lidar and similarly the statistics of the visibility. As is usual in the summer Arctic, low clouds are common; note that the cloud fraction for the 2nd lowest cloud layer refers to the remaining part of the sky, hence the total cloud cover is 76% percent plus 29% of the remaining 24, hence 83%, not considering even more layers. Fog is also quite frequent, occurring > 25% of the time, but when fog is not present haze is uncommon and the visibility is better than 20 km for > 70% of the time.

Figure 13 shows time series of the daily probability function for the net surface energy budget, taken from the surface turbulent flux, incoming short- and longwave radiation, using surface temperature for upwelling longwave radiation and a photo-based assessment of surface albedo for upwelling shortwave radiation. The figure also shows the corresponding time series of air and surface temperature. The transition from summer melt to autumn freeze is quite clear around Day of the Year (DoY) 240-242. Also clear as are the rapid cooling events following drops in the surface energy budget, usually as a consequence of dissipation of low clouds. Note that temperature variations, i.e. the time derivative of temperature, is a function of the net surface energy budget. Hence a change of sign in the energy budget does not lead to an immediate warming or cooling, as the time history of the budget is important. More information on the deployment, all instruments and the scientific results will follow in scientific publications.

A second deployment was performed as a part of the 2019 Ryder expedition (AO2019). For this deployment, not having any other atmospheric mission and with the good experiences from AO2018, we deployed the same instruments as on AO2018 but unattended. This data is under processing and will likely be released during the first half of 2020.

2.7.2. Description of provided data

The data from this and all deployments is openly available at the Bolin Center for climate research (www.bolin.su.se/data). In essence the target is to characterize the atmospheric column from the surface of the ocean though the troposphere with respect to both state variables, dynamic variables and fluxes. The different published datasets are explained in meta data and in readme-files along with the data, and the number of observed variables and derived quantities is too large to list here.

The dissemination is through the data and in scientific publications and in collaboration with national and international met services to provide data for data assimilation and for model assessment and evaluation.

2.7.3. Plans for the final implementation

During 2020 we will install the Doppler cloud radar and the scanning microwave radiometer, that we have spent part of 2018 and most of 2019 procuring, on Oden for two different missions. In June and July, the Oden will do a resupply mission to the Polarstern for *MOSAiC*, giving us four transects from Tromsö to wherever Polarstern is located at that time. This will be followed by the Swedish contribution to the *Synoptic Arctic Survey (SAS),* six-to-seven weeks in the central Arctic close to northern Greenland.

3. Future plans for the final implementation of the observing system

Future plans of the MPG is the deployment of the flask sampler at the Ambarchik site: in the upcoming winter the MPG will try to solve the problems regarding to shipment and import of this instrument into Russia, with the aim to have the instrument ready for the shipment in Siberia in summer 2020. Meanwhile the flask sampler will continue the monitoring at the current site. UNEXE will ensure the continue monitoring of CO_2 and CH_4 fluxes, all the mereological variables, from the 5 eddy covariance tower in north slope of Alaska and the regular maintenance of it. Due to the harsh condition of the Region UNEXE will work in close collaboration with the UIC personnel to ensure a good data coverage also during wintertime. USFD will continue the observation of CO_2 and CH_4 fluxes from the 5 EC tower in a close collaboration with SDSU, and UNEXE. The USFD will evaluate the performance of the two new heated sonic anemometer (CSI_CSAT3BH) in winter 2019 and spring 2020 in the attempt to increase the data coverage compare to the previous version of sonic installed. The monitoring activities of CNRS- Takuvik will be maintained throughout the project: the data collected will be used to investigate the impact of Arctic greening on snow physical properties, permafrost thermal regime and its impact on soil carbon stocks. A second measurement campaign using the SVC-FMI spectro-albedomenter, recently installed, will be carried out in March-April 2020, to refine and test the developed procedure. The microwave systems at FMI-ARC is still semi-operational: further development during the second filed season will involve the use of a fixed schedule and measurement protocol that will allows to provide a time series of continuous of continuous observations. No other aircraft observations are foreseen within the INTAROS project. The MISU will install during 2020 a Doppler cloud radar and a scanning microwave radiometer onboard of the Swedish research icebreaker Oden for two upcoming mission foreseen for June and July from Tromsö to the location of Polarstern. This will be followed by the Swedish contribution to the *Synoptic Arctic Survey (SAS),* six-to-seven weeks in the central Arctic close to northern Greenland.

4. Summary

The Deliverable 3.9 focused on atmospheric observation of the main greenhouse gases fluxes (CO_2 and CH_4) using ground, mobile and airborne eddy covariance observations to determine the atmospheric concentrations and fluxes as well as the boundary layer composition in North slope of Alaska, Canada, Siberia and Sweden. The development of a low-maintenance atmospheric observatory onboard of the Swedish research icebreaker Oden allowed continuous observation of the incoming broad-band radiation, surface temperature, and cloud-base lidars. Atmospheric Trace gases (e.g. N_2O, SF6, CO, O_2/N_2) were monitored using a flask sampler that allow automated collection of air samples under standardized conditions improving our ability to constrain atmospheric transport and surface-atmosphere exchange processes across the Arctic Regions. A series of climate-relevant variables of the atmosphere, snow and soil properties were collected along a transect of sites located in Northern Quebec with the objective to investigate the warming-induced effect on vegetation growth, snow properties, and permafrost thermal regime. The installation of a spectro-albedometer in March 2019, at the Sodankylä site will ensure continuous observations of surface albedo spectra in the 350-2500 nm wavelength range at 3-10 nm resolution. The installation of a SodScat radar, Elbara-II and SodRad radiometer systems were installed at the FMI-ARC site: these radiometers will provide continuous measurements of the active and passive microwave response of the boreal forest landscape in controlled condition.

--END OF DOCUMENT --

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