Towards an integrated data-driven infrastructure (InfraNor)

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1. Introduction

The Arctic is warming almost four times faster compared to the rest of the world (Rantanen et al. 2022). Svalbard and its surroundings have warmed faster than most of the Arctic (Cai et al. 2021; Isaksen et al. 2022). The Svalbard archipelago also shows large temperature variations from south to north and east to west (Østby et al. 2017). Svalbard has good infrastructure, logistics and communications (airport, port, laboratories), and excellent possibilities for data transfer. This makes Svalbard and its surroundings an attractive living natural laboratory for long-term and campaign-based Arctic studies.

Svalbard Integrated Arctic Earth Observing System (SIOS) is a Norwegian-initiated international cooperation to exploit Svalbard's research infrastructure for the purpose of increasing knowledge about global climate and environmental changes through long-term monitoring (Christiansen et al. 2024). It currently includes 29 member institutions from 10 different countries with a research focus relevant to interdisciplinary earth system studies in and around Svalbard. These studies explore the complex interrelationships between ocean currents, atmospheric and geological conditions, the extent of ice and snow, and terrestrial food webs of plants and animals. Within SIOS, researchers collaborate by sharing and integrating data and research infrastructure to build an efficient observing system that focuses on long-term monitoring of parameters that are important for understanding the Arctic in the context of global environmental change.

The research infrastructures[1] in Svalbard have mainly been established as independent activities by projects or research stations. The existing environmental monitoring and observation infrastructures in Svalbard are generally maintained at a high standard and are state-of-the-art. While the individual observations and research infrastructures might be of good quality, they are not optimised and the gathered data are not harmonised, except for e.g., in COAT (Pedersen et al 2025). SIOS utilises existing infrastructure, as well as new infrastructure, instigated by considerations and deliberations of the working groups coordinated by the central hub, SIOS-Knowledge Centre.

SIOS-InfraNor is a regional distributed observing system utilising versatile infrastructure from in situ to satellite remote sensing observations (Figure 1). The project, funded jointly by the Research Council of Norway and the Norwegian Space Agency (NoSA), strengthens SIOS with a coordinated and state-of-the-art observation network for marine, terrestrial and atmospheric research. This network, which provides data in accordance with the FAIR principles (Wikinson et al. 2016), is implemented and operated in and around Svalbard. The InfraNor project, as a prioritised infrastructure initiative identified through a gap analysis study, provides new and upgraded research facilities to support addressing Earth System Science (ESS) questions on global environment change. SIOS offers a single point of access to infrastructure, data, tools and services owned or operated by its members.

InfraNor is a response to the ongoing effort to optimise the SIOS observing system. This effort builds on the SIOS Strategy for Optimisation, and draws on work conducted through the SIOS Science Optimisation Service[2] (as described in the SIOS current state document[3]). The focus is on observational measurements to address regional issues and offer an opportunity for much more comprehensive monitoring of ESS-relevant variables throughout the region as articulated in the SIOS Infrastructure Optimisation Report[4]. The report targets vertical and horizontal interactions, cryosphere–geosphere dynamics, and climate change impacts on biodiversity and ecosystems.

1 https://research-and-innovation.ec.europa.eu/strategy/strategy-research-and-innovation/our-digital-future/european-research-infrastructures_en
2 https://sios-svalbard.org/Optimisation
3 https://sios-svalbard.org/sites/sios-svalbard.org/files/documents/2024-09/20240909_sios_currentstate.pdf
4 https://sios-svalbard.org/system/files/common/Documents/D3.4_SIOSInfrastructureOptimisationreport_PP.pdf

In order to be consistent with the thematic division in the Norwegian SIOS prioritisation report (Mehlum et al. 2013), we divided SIOS-InfraNor into 6 modules: Modules 1-4 contain scientific infrastructure priorities related to studies of atmosphere, land, ocean, and interdisciplinary research, Module 5 deals with data management, and Module 6 with project management.

The aim of this chapter is to present the main components of each module's implemented InfraNor monitoring system. It highlights the key items, outlines their characteristics, provides specimens of the collected datasets, along with references to selected novel scientific results published thanks to this infrastructure.

Furthermore, it explains how the system integrates data into a distributed coherent observing system that is addressing the needs of ESS as outlined in the SIOS Strategy for Optimisation, the SIOS Vision and the SIOS Strategy. A key component of this integration is the SIOS Data Management System[5] (SDMS), which acts as a bridge between the various science components of the Earth System through standardised and harmonised exposure of the collected data. The combined effect of this approach facilitates interdisciplinary science and enhances collaboration.

A list of acronyms used in this chapter is provided in Appendix 1.

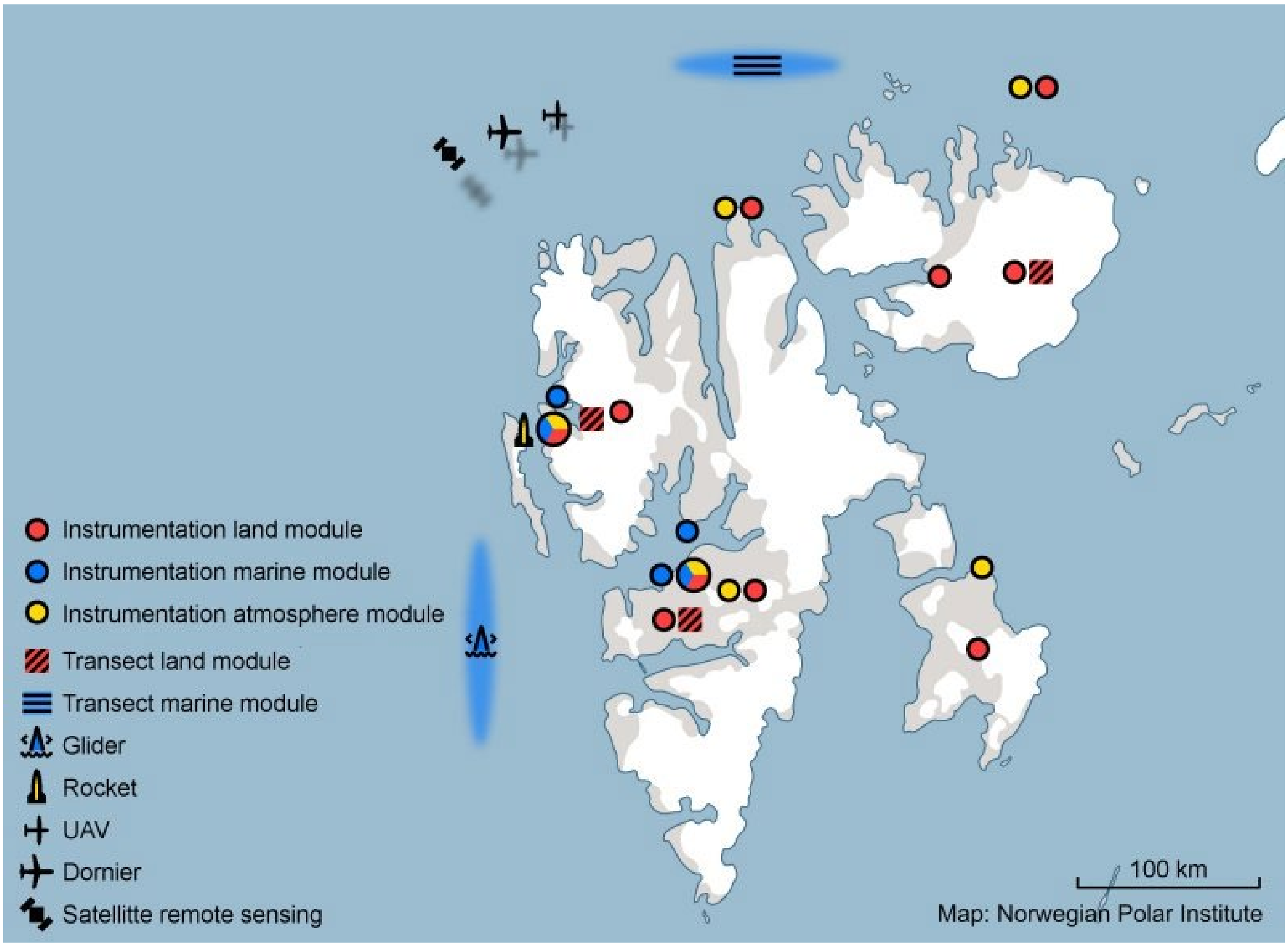

Figure 1: The InfraNor distributed installations within the atmosphere, terrestrial, ocean and common modules. Map by Anders Skoglund (NPI).

5 https://sios-svalbard.org/Data

2. Overview of the modules and their achievements

2.1. Module 1 – Atmosphere

This module focuses on enhancing and expanding observations of meteorology, climate, surface energy/radiation processes, and trace gas and aerosol characteristics. It also addresses air pollution transport to the Arctic and aims to improve understanding of the coupling between space and the upper and lower atmosphere, particularly in the polar region. Meteorological observations are essential parameters for other modules, supporting studies of land and ocean–atmosphere interactions and aiding in the assessment of climate impacts across the Arctic environment.

The module includes: 1) upgrading of the automatic weather stations (AWS) at Verlegenhuken and Edgeøya with radiation and snow depth measurements, combined with permafrost boreholes of Module 2; 2) upgrading the SOUSY Svalbard Radar in Adventdalen to continue the time series on polar mesospheric summer echoes (PMSE) and tropopause height; 3) resuming ionospheric soundings in Ny-Ålesund with a CADI-ionosonde to monitor the ionosphere for space weather and radio propagation conditions; 4) installing an Aerodynamic Particle Sizer (APS) at Zeppelin station to measure coarse (dust) aerosols; 5) installing and upgrading a Lunar Precision Filter Radiometer (PFR) instrument that measures the aerosol optical depth (AOD) making use of the moonlight methodology (Mazzola et al. 2024); 6) installing a Pandora instrument measuring atmospheric columns of trace gases, the two latter both at the Sverdrup station. The upgrades and installations of the atmospheric infrastructure took place from 2018 to 2021, and all the instruments have been operational for several years. Data are openly available in various international repositories and linked to the SIOS Data Management System (SDMS).

The observations enabled by InfraNor have proven to be valuable in several areas, including:

- The upgrade of the AWS provides important new data on surface–atmosphere energy exchanges at 80°N, at the northernmost point of Spitsbergen, Svalbard (Isaksen et al. 2022).
- The upgrade of the SOUSY radar continues one of the longest time series (since 1998) on PMSE (Hall et al. 2020) and in Feb. 2024, polar mesospheric winter echoes (PMWE) were observed for the first time. As a biproduct of the upgrade, the radar is now also capable of measuring vertical winds in the troposphere.
- The CADI ionosonde data are extensively used in both space weather applications and ionospheric research and for diagnosing high frequency (HF) radio conditions.
- The study of vertical coupling processes in the atmosphere, from the ground to space, includes not only data from the SOUSY radar and CADI ionosonde, but also rocket-borne process research from the CGI-cusp initiative. Data from CGI-cusp is being integrated with InfraNor data within the SDMS to address knowledge gaps in the SIOS initiative related to energy transport through the atmosphere (Moen et al. 2019).
- The APS has increased the size range in the size distribution measurements, making it possible to detect larger aerosols especially important during the arctic haze period and for detecting dust episodes (Platt et al. 2023).
- The lunar PFR has enabled measurements during the polar night, allowing for the analysis of annual cycles and year-round trends in AOD in the Arctic, which is rarely done (Platt et al. 2023).
- The Pandora instrument is fully operational in validating the ESA Sentinel-5P satellite (Compernolle et al. 2024). The validation of NO_2 has significantly improved due to parallel instrumentation. For O_3, measurements can now be taken year-round, whereas older instruments often stopped at lower azimuth levels (Svendby et al. 2024).

An example of a data product available from module 1 is shown in Figure 2.

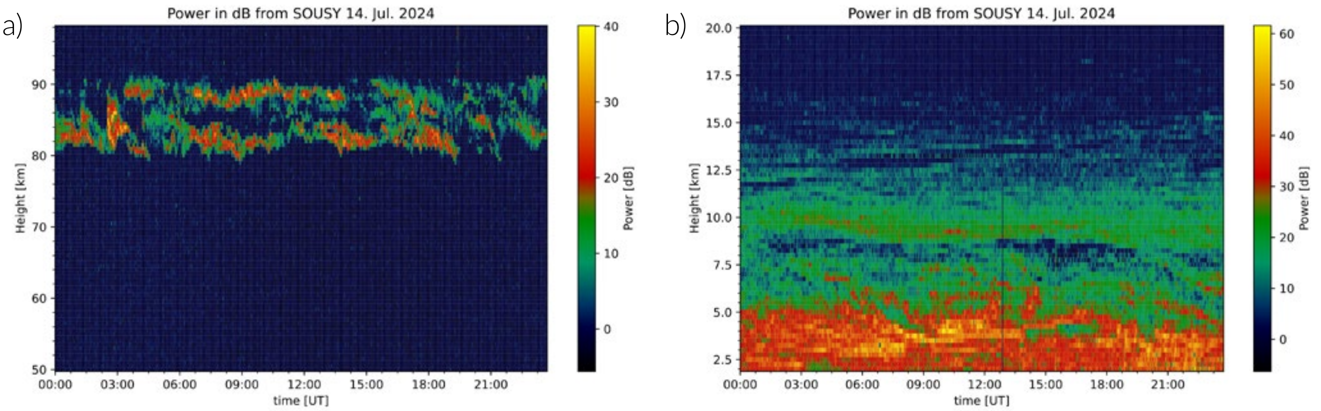

Figure 2: Raw backscatter signals in dB from the SOUSY Mesosphere Stratosphere Troposphere (MST) radar in Adventdalen from 14 July 2024. (Njål Gulbrandsen). **a)** Polar Mesospheric Summer Echos (PMSE), a strong radar backscatter in the mesosphere due to charged dust and ice particles that only happens in the summer when the temperatures in the mesosphere are low enough for ice formation. **b)** Radar backscatter from the troposphere due to dust, fluctuating temperature and humidity, and turbulence. Especially visible is the tropopause seen around 10 km. The radar is also capable of measuring vertical wind in the troposphere.

2.2. Module 2: Land

2.2.1. The SIOS terrestrial module

The SIOS land module implements an ecosystem and landscape-based observatory that focuses on key components of both predictor and driver targets. The monitoring covers different parts of the Svalbard landscape in the cryosphere, hydrosphere, and biosphere to enable real-time detection, documentation, understanding and prediction of climate impacts on Arctic tundra ecosystems. The infrastructures are implemented through a suite of instruments and study designs (Figure 3 and Pedersen at al. 2025). The module incorporates the *Climate-ecological Observatory for Arctic Tundra* (COAT; see Pedersen et al. 2025; Ims et al. 2013, Ims and Yoccoz 2017) and 15 separate instruments/infrastructures across eight institutions. This infrastructure provides detailed data for coupled process modelling at relevant temporal and spatial scales for the terrestrial ecosystem, as well as observations from the climatic gradients in Svalbard for larger scale studies and Earth System models. The implemented research infrastructure has both expanded and strengthened existing monitoring programmes, such as the Environmental Monitoring of Svalbard and Jan Mayen and the Global Terrestrial Network on Permafrost (GTN-P). Additionally, it provides new time-series and research infrastructure for focal ecosystem components and drivers that were previously lacking, such as snow monitoring.

Glaciology

Glaciers cover about 60% of the Svalbard archipelago and have lost significant mass over the last few decades. In situ measurements of mass balance are labour-intensive and thus limited to a few glaciers. Nevertheless, such direct measurements are essential to constrain and evaluate remote sensing products (e.g., Morris et al. 2022; Gray et al. 2015) and model simulations (e.g., Schmidt et al. 2023; Van Pelt et al. 2019; Østby et al. 2017) that are used to assess the state of balance of Svalbard glaciers on a regional scale (pan-Svalbard, Schuler et al. 2020). The infrastructure investments made by InfraNor and related SIOS-optimisation services permit now close-to-real-time records of glacier mass balance components, snow depth, snow and firn temperature profiles and surface flow velocity. Some of these essential variables related to the cryosphere are already accessible as quality-controlled datasets through the SIOS data portal; for the remaining records, such data publication currently is prepared or in progress. (Schuler et al. 2022; NPI-UiO, 2023). Near-surface measurements of meteorological variables (e.g., Schuler et al. 2013) also play an important role in filling the gaps in otherwise data-sparse regions, outside the coverage of operational weather-forecasting networks.

Snow

Snow is a critical component for Arctic climate and ecosystems, particularly in Svalbard, with a strong oceanic influence. The land module has established Svalbard as a much-needed (Christensen et al. 2023) super-site for calibration–validation of Arctic snow monitoring by implementing infrastructures on the ground and maintaining time-series of satellite remote sensing of snow parameters and field measurements. Several new automatic stations for snow depth measurements distributed across Svalbard and the COAT climate monitoring network significantly contribute to understanding the distribution of snow (cross reference to COAT chapter). SIOS has also established new relations between modellers and observers. The results of decadal intercomparisons have been documented in several scientific papers and in SESS reports (Vickers et al. 2020, 2022).

The land module has established field monitoring of the most important snow–climate variables, snow cover fraction (cameras), snow depth and snow water equivalent (ground penetrating radar). In addition, we have also established long term remote sensing time-series of additional parameters, such as snow wetness and avalanche activity. These parameters are crucial for understanding the effects of climate change in Svalbard. This infrastructure, together with extensive field campaigns during the years 2018–2023 has provided a significantly enhanced snow observation regime in Svalbard that has been documented as FAIR data in the SIOS Database.

Hydrology

The land module has established one new discharge station in the outlet of Linnévatnet lake, on the coast of Nordenskiöld Land; the Bayelva station, at the west coast close to Ny-Ålesund Research Station, has been reestablished because the old station was damaged due to the thawing of permafrost; and the De Geer station, in Nordenskiöld Land close to Longyearbyen, has been upgraded to improve data quality. The upgraded station is important in the continuation of the long-term hydrological monitoring series. The new station contributes to the Kapp Linné Environmental Observatory (KLEO) (Retelle et al. 2019). With the establishment, we have ensured that accurate discharge measurements continue from existing gauging stations, as well as from a new station. The continuation of the existing long-term discharge series and the establishment of new ones are critical for monitoring hydrological changes, as highlighted by Nowak et al. 2020. Data from all SIOS InfraNOR discharge stations are submitted to the Norwegian Water and Energy Directorate's Hydra 2 database and published in near real-time[6]also be included in the SIOS data management system, adhering to the FAIR principles.

Permafrost

Permafrost in Svalbard is widespread and traditionally classified as continuous, except under the larger glaciers. It is the warmest this far north in the Arctic (Romanovsky et al. 2010) and the longest existing record (from the Janssonhaugen permafrost monitoring site in Adventdalen, close to Longyearbyen) shows a distinct warming trend (Isaksen et al. 2022). The thermal state of permafrost in different landforms has only been monitored since the International Polar Year in 2008, and mainly in central Svalbard and only in the top layers of the permafrost typically down to 10 m depth. Very little data had been collected on the amounts and types of ice in the permafrost (cryostratigraphic studies), despite this being crucial to understanding the potential effects of climate change on the different parts of the Svalbard landscape. To be able to monitor the thermal conditions below the depth of the annual thermal variation, we have drilled 218 m in 8 boreholes, all with temperature observations down to 20 m depth in the Adventdalen area, in different landforms. The infrastructure in each borehole consists of a 20 m thermistor string with 25 sensors installed in a 21

6 https://sildre.nve.no

m long PVC casing. Also, a borehole that almost penetrates the permafrost in Adventdalen reaches down to 101 m (Figure 3) (Christiansen 2024). Boreholes have also been drilled at more remote locations: at Verlegenhuken, the northernmost point of Spitsbergen, and at Edgeøya - Kapp Heuglin in eastern Svalbard in connection with the operational automatic weather stations run by MET Norway. Co-locating these stations increases the value of permafrost data for researchers, model developers, and other users who require the most recent data, as it links directly to a national weather station that allows for quick and easy access (Isaksen et al. 2022). Data transfer occurs every 6 hours through the GSM mobile network or Iridium satellite communication directly to MET Norway in Oslo or downloaded annually if outside mobile and satellite phone coverage. Data is available in near real time in the cryo-web portal[7] and is under integration with SDMS following the FAIR guiding principles and the standards required for SIOS Core Data.

Permafrost cores have been obtained from fine-grained sediment to diamict with large clasts in blockfields from all of the boreholes, which have provided information on the ice content, type and age of the permafrost in different parts of the Svalbard landscape (Christiansen et al. 2021). These cores have been obtained using the UNIS medium-sized permafrost drill rig (Figure 3), which has been upgraded to be able to drill in these various sediment types that exist in Svalbard, including coarse-grained slope sediments that could not be cored previously.

With the extended boreholes the depth of zero annual amplitude (ZAA ≤ 0.1°C) has been reached at all borehole sites. The geothermal gradient varies in the 100 m deep borehole in Endalen from 0°C/m from the depth of ZAA down to 50 m depth (Figure 4), and below there increases to a maximum of 0.037°C/m from 90 to 100 m depth. This shows very clearly that the ongoing warming has reached a depth of around 50 m at that site.

Biosphere

A key to predicting Svalbard tundra ecosystem responses to drivers of change is a thorough understanding of the functioning of food webs (Legagneux et al. 2012, Mellard et al. 2021). The *Climate-ecological Observatory for Arctic Tundra* (COAT), a core of the SIOS biosphere monitoring, has implemented research infrastructure to facilitate data-driven causal analyses and short-term predictions (see chapter 7 – cross-ref to COAT chapter). One major outcome obtained from the

a) b) c)

Figure 3: The land module contains infrastructure established by the Climate-ecological Observatory for Arctic Tundra plus 15 separate instruments/infrastructures across eight institutions. A few examples are shown here. **a)** Automatic weather station operated on Etonbreen, Austfonna recording near-surface temperature, relative humidity, wind direction and speed, radiative fluxes, as well as snow height and air temperature. These are transmitted to University of Oslo for quality-control and analysis. Solar panels and a wind-turbine provide sustainable energy to power the recording and transmission systems. (Photo: Thorben Dunse). **b)** Field campaign in Adventdalen using drone with ground penetrating radar to measure snow depth over extended areas. (Photo: Eirik Malnes). **c)** The InfraNor upgraded UNIS medium-sized 3 m high permafrost drill rig (Photo: Ullrich Neumann / Kolibri GeoServices).

7 https://cryo.met.no

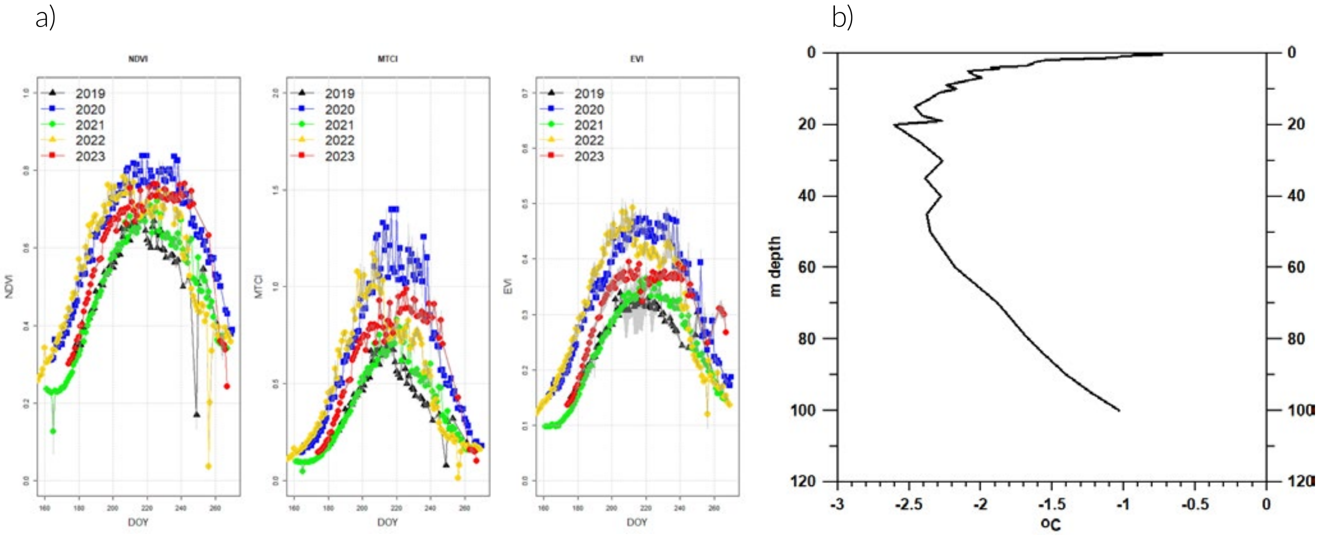

Figure 4: The land module has resulted in numerous scientific results, exemplified here by two important aspects of climate warming, namely Arctic greening and permafrost thawing. **a)** Annual Measurements of different greening-related parameters (NDVI, MTCI [MERIS Terrestrial Chlorophyll Index], and EVI [Enhanced Vegetation Index]) extracted from the hyperspectral FLoX (i.e., hyperspectral field sensor) system for the growing seasons of 2019–2023. The MERIS terrestrial chlorophyll index (MTCI) is sensitive to chlorophyll content (Tømmervik 2024). **b)** Average ground temperature showing the geothermal gradient down the 100 m deep borehole in Endalen. Data from the period November 2021 to November 2023 (Christiansen 2024).

pool of data from the module, was the evaluation of the high-Arctic tundra ecosystem conditions (Pedersen et al. 2021) where one of the main findings is that while the cryosphere and climate have undergone clear changes, the biosphere responses are less pronounced, and biological change may be lagging behind the climatic changes.

Karlsen et al. (2024) report a recent rapid and strong increase for Svalbard tundra productivity (MaxNDVI, Normalised Difference Vegetation Index) strongly related to the recent air temperature increase during the growth season. The high tundra productivity observed in 2022 through remote sensing methods is corroborated by in-situ hyperspectral measurements (Tømmervik et al. 2023; Figure 1). Trends noted through monitoring by near-surface NDVI and hyperspectral sensors in the period 2015–2023 (Karlsen et al. 2021; Parmentier et al. 2021; Karlsen et al. 2022; Tømmervik et al. 2023) were similar to those reported by Karlsen et al. (2024).

2.2.2. Module 3: Ocean

This module focuses on enhancing the marine infrastructure needed for better temporal and spatial coverage around Svalbard to capture the rapidly changing Arctic marine environment. The network of ocean observatories combines fixed observatories with mobile autonomous vehicles to record long-term time series for monitoring climate change and long-term trends, and short-term, high-resolution spatial studies. The observatories monitor areas like the Arctic Ocean inflow west and north of Svalbard and shelf-fjord regions along the West Spitsbergen coast, including physical and biological oceanographic coupling; structure and variability of ocean currents; ocean nutrients and pollutants (horizontally, vertically and through the food chain); and ecosystem resilience to climate seasonal variability and long-term change.

The module includes: 1) Long-term monitoring of the Atlantic Water inflow to the Arctic Ocean and onto the continental shelf and fjord areas through the A-TWAIN mooring array north of Svalbard (NPI/IMR) and the oceanographic mooring in Kongsfjorden (UiT), respectively; 2) Monitoring of changes of temperature, salinity, and circulation pattern in Isfjorden and Adventfjorden through the UNIS Online mooring (Figure 5a) and the NIVA mooring, respectively; 3) Improved spatial coverage of ocean observations by using gliders (Figure 5b) ranging from deep waters, over the continental slope, to the shelf, to understand the dynamics and variability of the current carrying warm Atlantic water toward the Arctic Ocean and the exchange mechanisms important for Atlantic Water intrusion towards the Arctic fjords; 4) Tracking methane release and other greenhouse gas exchanges from the seafloor (continental shelf) to the sea surface using observatories such as the K-Lander system; and 5) Attaining better understanding of physical and biological coupling by adding biological and biogeochemical instrumentation to the infrastructures listed in 1)-4).

The upgrades of existing marine infrastructure, and the purchase and deployment of new observation platforms, took place from 2018 to 2023. All infrastructures have provided data (except the K-Lander) and been operational for several years. Data are openly available in various international repositories, linked to the SIOS Data Management System (SDMS), and have been used in several publications.

The observations enabled by InfraNor Module 3 have proven to be valuable in several areas, including:

- The upgraded sensors on the mooring array north of Svalbard to measure Arctic Ocean inflow have provided data of physical, biochemical and biological relevance (Sundfjord et al. 2022).
- Moorings in Kongsfjorden (which have produced the longest marine time series in Svalbard) were upgraded and new moorings were acquired to collect data in Isfjorden (southern side close to the Svalbard airport) and Adventfjorden (close to the Adventfjorden river delta) for physical, biochemical, and biological time series studies (e.g., Hop et al. 2019; Cottier et al. 2018, 2021; Skogseth et al. 2020).
- An online mooring was installed in Isfjorden. Although the acoustic transfer of ocean data to a surface buoy was unsuccessful, the surface buoy gave valuable real-time observations of sea surface temperature, sea surface salinity, ocean waves, and meteorological parameters (wind speed and direction, air pressure, relative humidity, dew point temperature).
- Complementary measurements of biogeochemical parameters in the fjord close to the Adventfjorden river delta and from the river delta upstream (old Aurora station in Adventdalen) increased our understanding of land–ocean interaction processes.
- A new ocean glider, a 1000-m rated Teledyne Webb Slocum electric glider equipped with a pumped CTD system, was acquired and integrated into the glider pool and operations of the NorGlider facility coordinated by the University of Bergen. These gliders collected temperature and salinity profiles in waters around Svalbard.
- The SIOS InfraNor glider infrastructure has been available to the SIOS Access call since 2023 and was used by UNIS in 2023 and 2024 through the SIOS Access project "Spitsbergen Ocean Front Transect (SOFT)", providing valuable temperature and salinity profiles to study fjord circulation.

Scientific results from the InfraNor fixed mooring infrastructures (A-TWAIN, Kongsforden and Isfjorden) have been summarised in the ARiS chapter (Bensi et al. 2025). The integration of stationary fixed observatories with mobile autonomous vehicles provides unique insights into the factors that influence the dynamics of the marine environment around Svalbard. These insights include physical and biological oceanographic coupling, the structure and variability of ocean currents, ocean nutrients and pollutants (horizontally, vertically, and through the food chain); and ecosystem resilience to climate seasonal variability and long-term change.

Here we showcase the glider infrastructure. The glider is integrated into the glider pool and operations of the Norglider facility coordinated by the University of Bergen. This integration allows any available glider (Slocum or Seaglider) in the facility to be utilised for target transects or projects. The glider has been used to collect data in the West Spitsbergen Current off-shelf west of Svalbard as well as in Isfjorden (SIOS access project 2023 – SOFT_2023[8]) and the Barents Sea, supporting

8 https://sios-svalbard.org/SOFT_2023

a)

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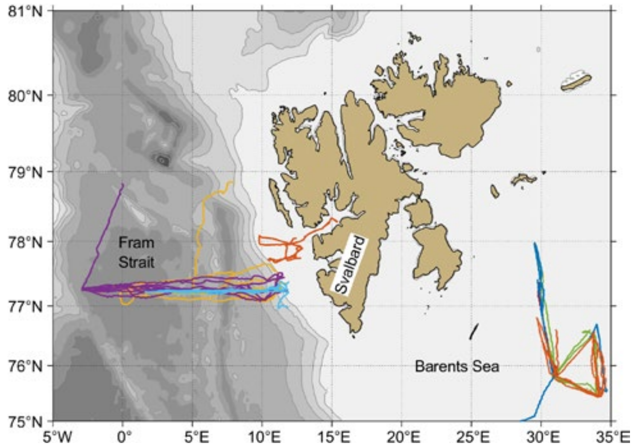

Figure 5: **(a)** UNIS Online Mooring in Isjorden. (Photo: Eva Falck) **(b)** Glider mission tracks in Fram Strait, Isfjorden and in the Barents Sea. Each coloured track represents a different mission. In Fram Strait, 3 missions repeatedly sampled the West Spitsbergens Current, and in the Barents Sea, 6 missions repeatedly sampled selected transects in the region. (Figure: Ilker Fer)

the Nansen Legacy activity. Data from these missions are available from Fer et al. (2021), Kolås et al.(2022), and Fer et al. (2024). The scientific results are reported in Kolås et al. (2020) and Kolås et al. (2024). The glider will continue to be available based on rentals and other financed activities.

Four successful deployments were made west of Spitsbergen, including one in Isfjorden. Since October 2018, the glider has conducted a total 518 science days (out of 537 total mission days) resulting in 2390 profiles. During these missions, 22 transects were obtained across the West Spitsbergen Current, between the prime meridian and the 400-m isobath at about 12°E. This dataset is presently being analysed to study the dynamics and variability of the current carrying warm Atlantic water toward the Arctic Ocean. Excluding targeted missions with microstructure probes in the Barents Sea polar front region, 6 standard glider missions were made in the Barents Sea between summer 2019 and fall 2022, with 403 days of science sampling returning more than 6000 profiles. Using the observations from the gliders, combined with observations from scientific cruises and a historical dataset compiled by UNIS (Skogseth et al. 2019), Kolås et al. (2024) presented detailed circulation pathways in the northwestern Barents Sea, and quantified that half of the Atlantic Water inflow through the Barents Sea opening between Svalbard and Norway reaches the Hopen Trench, and then subducts under polar waters and continues northward, steered by topography. Compared to 1980, the average Atlantic Water temperature in this region increased by 0.7°C and freshened by 0.1 g/kg, with implications for poleward transport of warm water.

2.2.3. Module 4: Common Infrastructure

In this module, we introduced new interdisciplinary research infrastructure that contributes unique capacities through collection of new data time series. The fact that the infrastructure and sensor capacities have applications in multiple domains lead to the creation of the Common Infrastructure Module.

Specific remote sensing products are identified as one of the common infrastructures of the SIOS-InfraNor project. Daily CMOD5 (for neutral winds) processing of high-resolution Sentinel-1 SAR wind fields was set up at the Nansen Centre. The wind fields were estimated from VV polarised medium resolution (40 m) SAR normalised radar cross section (NRCS) combined with wind directions from the AROME-Arctic forecast model, available from the Norwegian ground segment and the Norwegian Meteorological Institute. The wind fields for 2019 and 2020 are made available to SIOS via the OPeNDAP protocol on the THREDDS server at the Nansen Centre and are expected to be incorporated in the SIOS data catalogue.

A Svalbard-wide vegetation map has been generated as a common infrastructure using Sentinel-2 data. The Multispectral Instrument (MSI) onboard the satellites provide images with a resolution of 10, 20 and 60 metres. In this product Sentinel-2 A/B 14 images from the dates 2 August 2017 and 31 July 2017 are used in the map creation process. The final map is not yet available but is expected to be made available on SIOS data portal.

The main investment of this module was the establishment of the Dornier DO228 aircraft instrument pod, permanently stationed in Longyearbyen. This unique capability is a collaboration with Lufttransport AS whereby one of the firm's aircraft carries a permanently attached instrument pod housing state of the art sensors. This gives low-cost access throughout the year as there are no ferrying costs. The broadband long range communication system in the pod has allowed us to use the aircraft as a datamule transferring gigabytes of data from buoys within a 1000 km range. This is much more efficient than using an ice-breaker, reducing the environmental footprint of the research in addition to offering the possibility of real time data transfers to scientists in the field.

Key capabilities of the Dornier research Aircraft instrument pod[9]:

- Optical Imaging Sensors: The aircraft is fitted with hyperspectral sensors that capture data across 186 spectral bands in the range of 400–1000 nm and a 50 Mpix aerial RGB camera.
- High Resolution: The sensors provide a ground resolution of approximately 30 cm for the hyperspectral camera and 10 cm for the aerial RGB camera from an altitude of 1000 metres, covering about 600 metres across track.
- Georeferencing: With proper post-processing, the navigational data can achieve direct georeferencing with an accuracy of up to 0.5 pixels.
- Operational Flexibility: The aircraft is used for regular flights in the Svalbard region and can be chartered for specific research missions year-round.
- Future Expansion: There are plans to potentially include additional sensors such as a hyperspectral imager (SWIR 900-2500 nm), SAR sensor, thermal camera, and laser scanner.

There have been several campaigns where data have been collected since the platform became operational in 2020, supporting a wide range of studies within glaciology, vegetation and marine and coastal studies. Flight tracks for hyperspectral data capture are shown in Figure 6a. An example of use of the airborne data is presented by Błaszczyk et al. 2022, where the aerial data are combined with terrestrial laser scanning data to study geomorphological changes in the Hornsund area. Jawak et al. 2021 describes how the SIOS aircraft data products helped fill the data gaps caused by the Covid-19 pandemic travel restrictions and lack of in situ data acquisition in 2020.

Drone services are also part of the SIOS Research Infrastructure Access Programme. One example of how these services can be applied is collection of data on snow water equivalents using a drone mounted UWB radar (Eckerstorfer et al. 2018); another is use of a vertical take-off and landing (VTOL) drone to scout for icebergs from RV Kronprins Haakon in support of the SFI CIRFA cruise (Dierking et al. 2022). The drones are well suited for carrying custom sensor packages as they are based on open-source software which makes it easy to interface the data flow to the drone system and provide and inject essential metadata from the drone to the dataset, such as position, orientation and data from other sensors carried onboard. The multirotor drone currently available can carry up to 20 kg payload and has a flight time of between 10 and 45 minutes depending on payload weight. The VTOL drone can carry 2 kg payload for up to 2 hours and cover 100 km in a flight.

2.2.4. Module 5: Data management

The SIOS Data Policy promotes free and open

9 https://sios-svalbard.org/aerialRSplatforms

a) b)

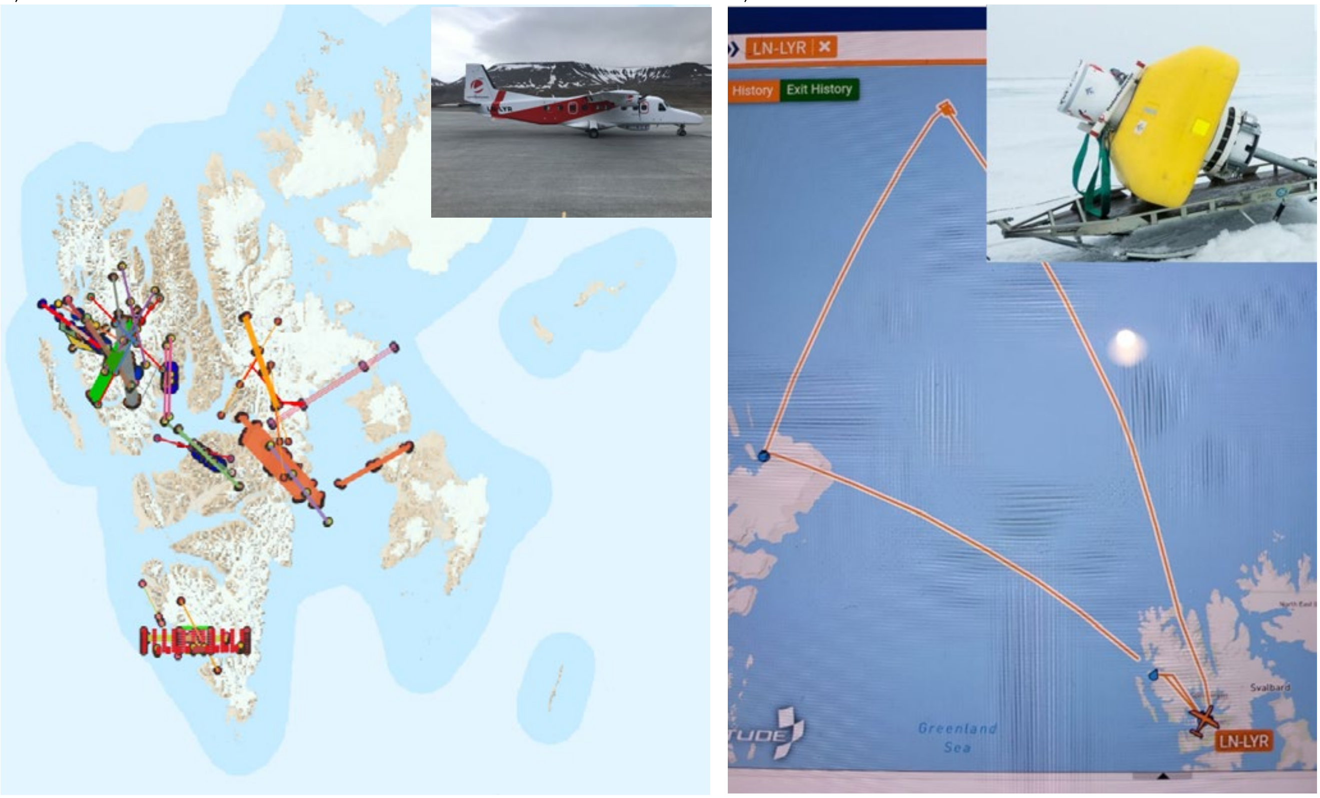

Figure 6: a) Flight tracks for Dornier hyperspectral data collection. (Photo: Agnar Sivertsen) **b)** Dornier as a datamule for the ArcticABC project. (Photo: Pedro de la Torre)

access to data. It is a requirement that scientists and projects utilising the SIOS Infrastructure also adhere to the SIOS Data Policy and deposit data in a data centre contributing to the SIOS Data Management System[10] (SDMS).

The main focus of SIOS-InfraNor data management has been to ensure that the data generated by the instrumentation funded are properly taken care of and shared through SDMS. SDMS is a physically distributed data management system where data are not hosted in a centralised location, but rather integrated through integration of data centres contributing to SIOS. Thus, to ensure a functional system, SIOS relies on agreed standards for documentation of and access to data. Utilisation of standards allows integration with discipline-specific (e.g., WMO Information System) and regional (e.g., Copernicus Marine Environmental Monitoring Service) data management systems. Development of the SDMS technical infrastructure is aligned with current efforts of, e.g., the combined SAON/IASC Data Committee and builds on the experience of distributed data management during the most recent International Polar Year.

SDMS is a physically distributed data management system tied together by discovery and harvest of metadata, which is similar to index cards in libraries, documenting what is measured, by whom, where, when and how it can be accessed. Sub-systems that do not comply with the agreed interoperability standards cannot be integrated. The lowest level of integration is unified data discovery. For this to be useful, harmonised terminology is essential for description of what is measured, and for identification of standardised data access mechanisms and documentation at the use level. If the latter parts are properly done by data centres contributing, it is possible to do on the fly visualisation, subsetting and transformation of datasets. An example of on-the-fly visualisation of data is provided in Figure 7 which shows the information from an automatic weather station on Etonbreen. Data are stored according to CF-NetCDF convention and served through an OPeNDAP server. This implies that the visualisation application can be operated by one data centre

10 https://sios-svalbard.org/Data

and the data served by another data centre. The user can choose if data are to be downloaded as NetCDF format or other formats (e.g., CSV for easy analysis).

Given the framework described above, the main emphasis during the project has been to improve integration of selected partner data centres and ensure proper documentation and publication of the datasets generated. All data collected during the project are supposed to qualify as SIOS Core Data and thus implicitly should be published in harmonised form using CF-NetCDF or Darwin Core Archives. This ensures that data easily and with the help of computers can be combined.

While proper documentation has been achieved for most of the datasets, some work is still pending in order to fully integrate all data through the data repositories handling them. When it comes to interoperability interfaces at partner data repositories, no major advances have been made during the project; interfaces are primarily as they were before the project started, with interoperability primarily achieved at the discovery level. This has been a challenge in SIOS since the start and in order to circumvent this, some datasets with a higher potential for integration across providers and with other data, and that have greater potential for reuse in community-wide services (e.g., EOSC and BlueCloud 2026) have been routed to data centres that have all interfaces in place. In addition, some already published datasets have been cached by these data centres in order to improve functionality. On a general basis there is a lack of understanding of what is needed of data management harmonisation in order to establish a coordinated network of observations (e.g., World Meteorological Organization, Global Biodiversity Information Facility) as opposed to the normally fragmented data documentation used in scientific communities.

While there have been challenges with harmonising data documentation for several datasets, this has succeeded for ocean data. The same applies to information from weather and permafrost stations as well as remote sensing data. Many of these datasets are documented using the standards required and are served through interfaces that allow integration into decision support systems or further processing. When it comes to biodiversity data – in this context essentially the ecosystem-based data of the Climate Ecological Observatory for Arctic Tundra (COAT) – only interoperability at the discovery level has been achieved, leaving no interoperability at the use level. For these datasets a human in the loop is required to understand the data collected and no services like on the fly visualisation can be offered.

Data generated by drones or the Dornier instrument pod have been a major challenge which is now addressed by data transformation tools allowing representation of point clouds in multiple forms, including CF-NetCDF as required by the SDMS Interoperability Guidelines. These data will be published as CF-NetCDF but users will have the ability to download data in other formats (as is supported, e.g., for timeseries).

Although there was a strong emphasis at management level on data management in the project, this focus, with a few exceptions, was not fully understood nor adopted at the instrument implementation level. The understanding of what the FAIR guiding principles imply is weak in the community. One potential cause could be that many observational scientists are more interested in their own data than in combining these with other data. The situation is quite different among scientists within remote sensing and numerical simulation as these often use data provided by others and see the benefit in harmonised documentation standards. Another explanation could be that the knowledge and skills to create good datasets are lacking. This could be compensated by training activities, which was not covered well in the project. This will of course only help if data providers understand the need for harmonised documentation in order to integrate data across data providers.

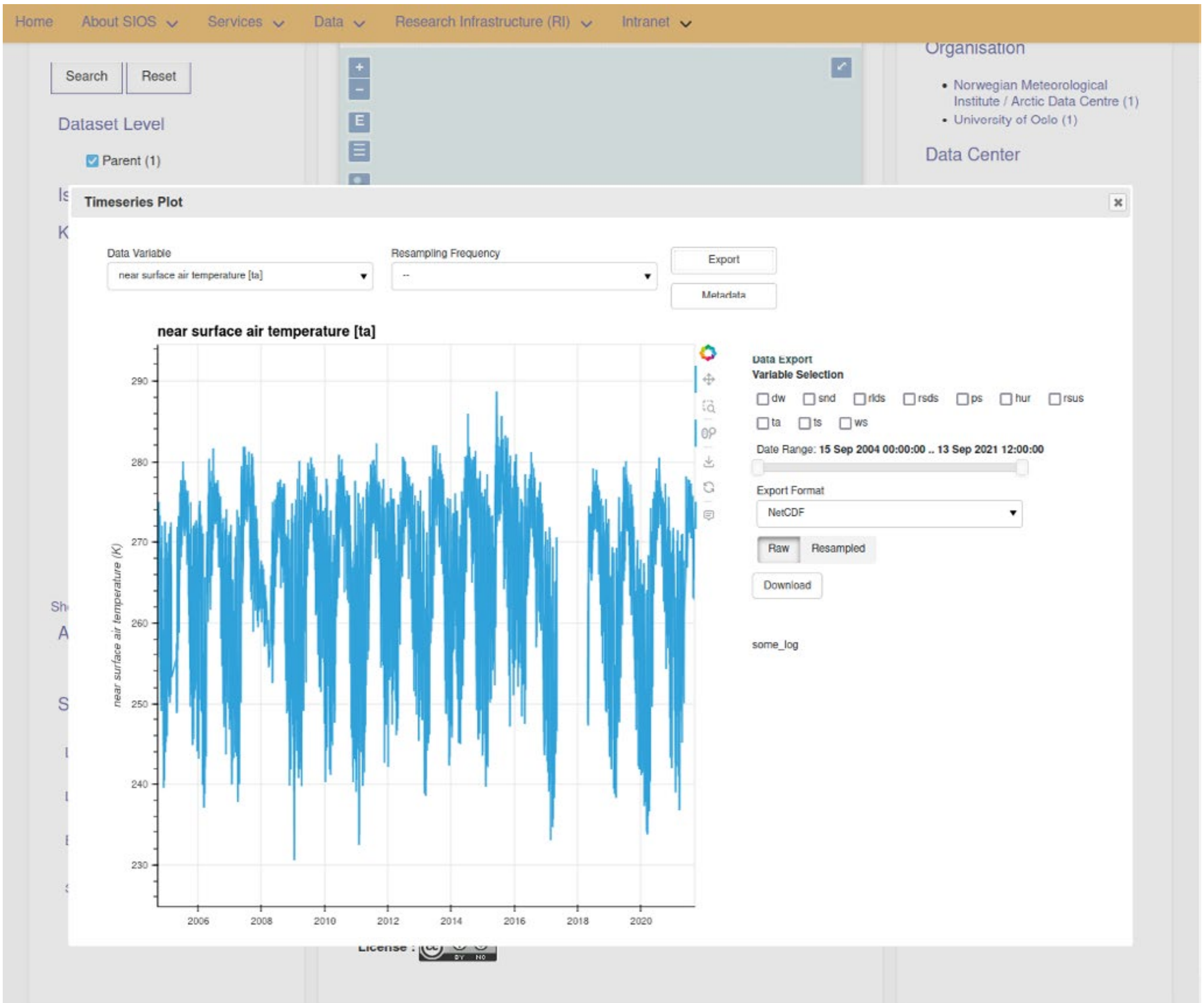

Figure 7: Screen dump of a dataset collected using an automatic weather station at Etonbreen. This is the visualisation available in the data portal if data are published in the appropriate form.

3. Contributions to interdisciplinarity

InfraNor's multidisciplinary nature enables interdisciplinary capabilities by combining co-located and distributed infrastructures, with their data integrated into the SDMS, thereby facilitating a holistic approach enhancing the understanding of Earth System Science. The SDMS links all the components, creating interconnections within the multidomain research infrastructure and paves the way for interdisciplinary studies.

Examples of interdisciplinarity can be found in all modules of InfraNor. A specific example is COAT (Pedersen et al 2025) within the land module, which is an adaptive ecosystem-based programme combining ecology and geophysics (e.g., meteorology, snow geophysics, climate-related monitoring, etc...), and thus contributing to conservation and management of climate-sensitive components of Norwegian Arctic ecosystems.

Permafrost boreholes have been established at remote COAT weather stations in Svalbard, forming an integrated monitoring system that provides daily updated data essential for examining and tracking current conditions, trends, and effects of extreme climate events on active layer thickness and permafrost temperatures.

The observation programme has been expanded to include measurements of soil moisture, near-surface soil temperature, snow depth, and surface irradiance. This approach fosters consistency and collaboration across national and international initiatives, reduces the environmental impact of the installation, and maximises the value of new stations.

As a result, permafrost data are better integrated and more accessible to climate, snow, and permafrost modelling communities, as well as remote sensing communities for calibration and validation (Isaksen et al. 2022).

The strategy also optimises MET Norway's operational value chain, enabling rapid and efficient data access.

The Common Infrastructure Module provides infrastructure and sensor capacities having applications in multiple domains to support cross-disciplinary priorities. Some infrastructures of the Ocean Module have been used for other projects such as the Nansen Legacy project (Fer et al. 2021, 2024; Kolås et al. 2022).

The multidisciplinarity that is conferred by the InfraNor multidisciplinary research infrastructure and the SDMS together with other projects that have made use of InfraNor has been treated in various previous SESS reports. This is presented in reverse chronological order in the following SESS chapters: SNOW 23 (Malnes et al. 2024); SATMODSNOW 2 (Vickers et al. 2024); SATS (Haaland et al. 2024, 2023); LOAD-RIS (Hansen et al. 2023); SCD (Matero et al. 2022); COAT (Pedersen et al. 2025, 2022, 2020); PermaSval (Christiansen et al. 2021, 2020, 2019); GROWTH (Karlsen et al. 2020); PASSES (Salzano et al. 2021); iMOP (Cottier et al. 2022, 2019); GCI Cusp (Moen et al. 2019).

4. Analysis of achievements

The recent upgrades and installation of advanced instrumentation have significantly enhanced long-term monitoring programmes, elevating the quality and sensitivity of these critical observations, further filling some critical observational gaps. The openly accessible data are utilised by numerous national and international organisations for informed policymaking and by scientists conducting in-depth analysis and research.

COAT has successfully demonstrated the use of the ecosystem-based data as a basis for evaluation of ecosystem condition of high Arctic tundra in Svalbard (Pedersen et al. 2021). COAT has successfully implemented research infrastructure for monitoring of five biotic food web modules and a climate monitoring network, consisting of eight full-scale automatic weather stations and more than 300 ground temperature loggers.

The remote sensing products have been produced for a defined/limited time-series: if extended further they will provide essential data for understanding long-term changes in Svalbard. The data produced by different modules should be fully exploited to address cross-disciplinary questions.

The Dornier platform is a powerful tool to gather vast amounts of hyperspectral and RGB aerial data, with extremely high resolution and position accuracy. That in itself is also a challenge when it comes to distributing and analysing the data. We are still working on improving accessibility on both points. The other challenge is to increase the use of the platform: costs associated with chartering the aircraft and user co-pay requirements limit its use. During the Covid-19 period the aircraft was one of few ways to gather data during lockdown and travel restrictions, and we saw increased use (Jawak et al. 2021). The model of combining passenger aircraft, logistics and science has made this an extremely cost-efficient tool available year-round as it is based in Longyearbyen. The drone infrastructure also has capacity for more use, the main challenge here as well is the need for co-funding by users.

Tremendous amounts of hyperspectral data collected by the instruments on the Dornier aircraft have made Svalbard one of the hyperspectral-rich data regions on our planet. The lessons learned from use of common infrastructure can be an example for Arctic observing systems on continuation of data series during natural calamities such as pandemic. Common infrastructure also inspired collaboration between scientists working in Svalbard.

A sharper focus on data management early in the process would be advisable. None of the universities in Norway has infrastructure in place to deliver data through SDMS (even after the project is finished). That makes it almost impossible to fulfil the demands of SIOS without a lot of ad-hoc solutions. The available national infrastructure is also missing this functionality. In many contexts, data centres have placed more emphasis on Findable and Accessible, than Interoperable and Re-useable, which is where the real benefit of data management lies. Work is in progress to compensate for part of this at some data centres, but these processes take much time. Mitigation through direction of data submission to data centres that fulfil SIOS requirements would solve the issue while other data centres improve their interfaces.

5. Recommendations for the future

- To monitor rapid climate shifts and their impacts in the Arctic, it is vital to secure long-term funding for Svalbard's observatories and ensure open, accessible, and well-documented data to foster collaboration and wider research use.
- Enhanced use of different levels of remote sensing (e.g., satellites, aircraft, drones) could be supported by various funding tools, e.g., transnational access support from EU, SIOS access programme. Higher-level product development and user training workshops would lower user barriers.
- The data produced by SIOS and supported by projects like SIOS-InfraNor should be evaluated against Copernicus service requirements in cross-disciplinary working group meetings. The recently published Copernicus Polar Roadmap 2024 highlights the evolution of these services.
- In reference to the updated Copernicus Roadmap and its recommendations, a re-analysis of observation gaps is strongly recommended.
- Further synergies should be sought by integrating SIOS InfraNor data (e.g., vegetation and snow data) as drivers of ecosystem change, particularly related to the long-term ecosystem-based monitoring done by COAT and other SIOS-related projects.

6. Data availability

See Appendix 2.

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Appendix 1: List of acronyms

AOD – Aerosol Optical Depth

API – Application Programming Interface

APS – Aerodynamic Particle Sizer

A-TWAIN[11] – Long-term variability and trends in the Atlantic Water inflow region

AWS – Automatic Weather Station

BlueCloud[12] – the Open Science platform for collaborative marine research

CADI – Canadian Advanced Digital Ionosonde

CF-NetCDF – Network Common Data Format (NetCDF) with Climate and Forecast (CF) standard naming convention

CGI-cusp – the Grand Challenge Initiative (GCI) Cusp initiative

CMOD5[13] – geophysical MODel function for ERS C-band scatterometry

COAT – Climate Ecological Observatory for Arctic Tundra

CTD – Conductivity, Temperature, and Depth (oceanographic measurement instrument)

EOSC – the European Open Science Cloud

ERS – European Remote Sensing Satellites

ESA – the European Space Agency

ESS – Earth System Science

EVI – Enhanced Vegetation Index

FAIR – Findable Accessible Interoperable Reusable

FloX[14] – Fluorescence boX (chlorophyll fluorescence observation instrument)

GSM – Global System for Mobile Communications

GTN-P – Global Terrestrial Network on Permafrost

IASC – the International Arctic Science Committee

ICI-5 – Investigation of Cusp Irregularities 5th mission

IMR – the Norwegian Institute of Marine Research

K-Lander[15] – Kongsberg Seabed Observatory

KLEO – Kapp Linné Environmental Observatory

MET – the Norwegian Meteorological Institute

MSI – Multispectral Instrument

MST – Mesosphere Stratosphere Troposphere

MTCI – MERIS Terrestrial Chlorophyll Index

NDVI – Normalised Difference Vegetation Index

NIVA – the Norwegian Institute for Water Research

NPI – the Norwegian Polar Institute

NRCS – SAR Normalised Radar Cross Section,

OPeNDAP – Open-source Project for a Network Data Access Protocol

PFR – Lunar Precision Filter Radiometer

11 https://www.npolar.no/en/projects/a-twain/
12 https://blue-cloud.org/
13 https://www.ecmwf.int/en/elibrary/74789-cmod5-improved-geophysical-model-function-ers-c-band-scatterometry
14 https://www.jb-hyperspectral.com/products/flox/
15 https://www.kongsberg.com/maritime/news-and-events/news-archive/2016/innovation-meets-new-modular-design-the-kongsberg-k-lander-mk2-seabed/

PMSE – Polar Mesospheric Summer Echoes

PMWE – Polar Mesospheric Winter Echoes

RI – Research Infrastructure

SAON – the Sustained Arctic Observing Networks

SAR – Synthetic Aperture Radar

SDMS – SIOS Data Management System

SFI CIRFA – Research-based Innovation (SFI[16]) Centre for Integrated Remote Sensing and Forecasting for Arctic Operations (CIRFA[17])

SOFT – Spitsbergen Ocean Front Transect

SIOS InfraNOR[18] – Svalbard Integrated Arctic Earth Observing System - Infrastructure development of the Norwegian node

SOUSY – SOUnding SYstem (MST Doppler Radar)

SWIR – Short Wavelength InfraRed

UWB – Ultra Wide Band

THREDDS – THematic Real-time Environmental Distributed Data Services

UiT – the University of Tromsø – the Arctic University of Norwa

VTOL – Vertical Take-Off and Landing

WMO – the World Meteorological Organization

16 https://www.forskningsradet.no/finansiering/hva/sfi/
17 https://cirfa.uit.no/
18 https://prosjektbanken.forskningsradet.no/project/FORISS/269927

Appendix 2: Data availability

Dataset	Parameter	Period	Location	Metadata access (URL)	Dataset provider
Etonbreen AWS	Meteorological parameters, snow height.	2004–2021	Etonbreen/ Austfonna glacier	https://doi.org/10.21343/9hez-nz67	Thomas V. Schuler (UiO), John Hult (UiO), Simon Filhol (UiO)
Remote sensing DOAS measurements	NO2	2020–2021	Ny-Ålesund	https://sios-svalbard.org/metsis/elements/no-met-adc-1e3b2283-bc95-5264-9ea1-d51101dc8bfa/search	Ann Mari Fjaeraa (NILU)
APS observations	Aerosol number size distribution	2021–2023	Ny-Ålesund Zeppelin mountain	https://doi.nilu.no/doi/3CZW-UGSH	Markus Fiebig (NILU), Chris Lunder (NILU)
moon tracking PFR	Aerosol optical depth (AOD)	2002–2023	Ny-Ålesund	https://sios-svalbard.org/metsis/search?search_api_fulltext_op=and&fulltext=PFR+NO0057R	Georg H. Hansen (NILU), Natalia Kouremeti (PMOD-WRC), Kerstin Stebel (NILU)
m-NLP on VISIONS-2	electron density (sounding rocket)	2022	Ny-Ålesund	https://sios-svalbard.org/metsis/elements/no-met-adc-28c940f3-bd99-50c2-aecc-f706652ac63e/search	David Michael Bang (UiO), Espen Trondsen (UiO), Andres Spicher (UiT)
Kongsvegen AWS	Meteorological parameters, snow height.	2021–2022	Kongsvegen	https://doi.org/10.21343/5ht4-bj50 (sw110) … https://doi.org/10.21343/1r1z-ae07 (sw250)	Simon Filhol (UiO), Pierre Marie Lefeuvre (NPI), Jean-Charles Gallet (NPI)
Midtre Lovenbreen AWS	Meteorological parameters, snow height.	2021–2022	Midtre Lovenbreen AWS	https://doi.org/10.21343/5ht4-bj50 (sw110) … https://doi.org/10.21343/5ht4-bj50 (sw140)	Simon Filhol (UiO), Pierre Marie Lefeuvre (NPI), Jean-Charles Gallet (NPI)
Hyperspectral measurements	Phenological parameters; SIF (Sun Induced Fluorescence)	2019–2023	Adventdalen	https://doi.org/10.21343/ZDM7-JD72	Hans Tømmervik (NINA), Lennart Nilsen (UiT)
Drone and Sentinel-2 NDVI in COAT	NDVI, biomass, disturbance, temperature	2018–2022	Adventdalen, Brøggerhalvøya, Sassendalen	https://doi.org/10.21334/npolar.2024.c048fa4c	Virve Ravolainen (NPI), Ingrid Paulsen (UiT)
Vegetation phenology	Phenological parameters;	2015–2023	Adventdalen	https://doi.org/10.21343/kbpq-xb91 (2021)	Lennart Nilsen (UiT), Hans Tømmervik (NINA).
COAT	State variables according to the Science Plan (Ims et al. 2013)	See Science Plan	Nordenskiöld Land Brøggerhalvøya, Kongsfjorden and surroundings	https://sios-svalbard.org/metsis/search?search_api_fulltext_op=and&fulltext=COAT https://data.coat.no/	COAT consortium

Dataset	Parameter	Period	Location	Metadata access (URL)	Dataset provider
A-TWAIN mooring	CTD, ADCP	2017–2020	Nansen Basin, Barents Sea	https://doi.org/10.21334/npolar.2020.e7041026 https://doi.org/10.21334/npolar.2022.d3a5adc2	Arild Sundfjord (NPI) et al.
InfraNor seaglider	Ocean currents, salinity, temperature	2020–2021	Fram Strait	https://doi.org/10.21335/NMDC-1878084716	Ilker Fer (UiB) et al.
InfraNor seaglider	Ocean currents, salinity, temperature, oxygen	2019–2021	Barents Sea	https://doi.org/10.21335/NMDC-381060465 https://doi.org/10.21335/NMDC-571158912	Eivind Kolås (UiB) et al. Ilker Fer (UiB) et al.
Isfjorden wave observations	Period, height	2020	Isfjorden	https://sios-svalbard.org/metsis/elements/no-met-adc-d9cd7110-3a31-587f-a890-c8833b879de6/search	Frank Nilsen (UNIS)
Ocean Colour Svalbard	Chlorophyll a	2022–2023	Svalbard	https://sios-svalbard.org/metsis/elements/no-nersc-b10c0759-0691-5e29-8a36-07a975dd373d/search	Anton Korosov (NERSC)
SAR avalanche detections	Polygon delineation of avalanche	2021–2022	Svalbard	https://sios-svalbard.org/metsis/elements/no-met-adc-767bf5fb-949d-5990-9fad-5ccd98254abb/search	Jakob Grahn (NORCE)
SAR Wet snow maps	Grid cells classified codes	2004–2024	Svalbard	https://sios-svalbard.org/metsis/elements/no-met-adc-abc1503f-74c6-55a1-b9e5-f0a3838c0492/search	Eirik Malnes (NORCE)
MODIS Daily Snow Cover	Snow Cover Fraction	2000–2021	Svalbard	https://sios-svalbard.org/metsis/elements/no-met-adc-fbb9d256-3387-54db-af38-4e94c2f8ba14/search	Eirik Malnes (NORCE)
UAV GPR Snow depth	Snow depth	2019–2022	Longyearbyen Nordenskjöld Land	https://doi.org/10.21343/zaw8-2g80	Rolf-Ole Rydeng Jenssen (NORCE)