ARGO: ARctic greenhouse Gas Observation metadata version 1

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Abstract. Our understanding of how rapid Arctic warming and permafrost thaw affect global climate dynamics is restricted by limited spatio-temporal data coverage due to logistical challenges and the complex landscape of Arctic regions. It is therefore crucial to make best use of the available observations, including the integrated data analysis across disciplines and observational platforms. To alleviate the data compilation process for syntheses, cross-scale analyses, earth system models, and remote sensing applications, we introduce ARGO, a new meta-dataset comprised of greenhouse gas observations from various observational platforms across the Arctic and boreal biomes within the polar region of the northern hemisphere. ARGO provides a centralised repository for metadata on carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) measurements linked with an interactive online tool (https://www.bgc-jena.mpg.de/argo/). This tool offers prompt metadata visualisation for the research community. Here, we present the structure and features of ARGO, underscoring its role as a valuable resource for advancing Arctic climate research and guiding synthesis efforts in the face of rapid environmental change in northern regions. The ARGO meta-dataset is openly available for download at Zenodo (https://doi.org/10.5281/zenodo.13870390) (Vogt et al., 2024).

1 Introduction

The Arctic region is experiencing rapid warming, with temperatures rising nearly four times faster than the global average (Rantanen et al., 2022). This accelerated warming has profound implications for the Earth's climate system, as the Arctic plays a critical role in regulating global climate dynamics. Of particular concern is the thawing of permafrost, perennially frozen soils, which are estimated to contain carbon stocks of at least 1,700 Pg (Miner et al., 2022; Schaefer et al., 2014; Schuur et al., 2022). This enormous carbon reservoir is at risk of being partially released into the atmosphere upon thaw, triggering an accelerating feedback loop that would further amplify global warming. Simultaneously, ongoing warming within the high northern latitudes holds the potential to trigger substantial changes to permafrost ecosystem characteristics, including climate-

induced vegetation changes that may lead to shrubification (Mekonnen et al., 2021), or changes in hydrology (Andresen et al., 2020; Heslop et al., 2020) that alter greenhouse gas flux patterns.

Quantifying the current Arctic carbon budget requires a comprehensive monitoring network across the Arctic. Furthermore, to facilitate accurate projections of its future evolution based on understanding the mechanisms that control carbon cycle dynamics, more in-situ data need to be integrated into process-based models (Watts et al., 2021; Natali et al., 2019). With Arctic landscapes being highly heterogeneous across spatial scales (Watts et al., 2021; Euskirchen et al., 2017; Virkkala et al., 2021a), a large number of observation sites would be needed to resolve the pronounced variability in greenhouse gas processes (Pallandt et al., 2022). However, the vast size of the Arctic region, in combination with logistical challenges linked to harsh climate conditions and scarce infrastructure, to date has permitted the establishment of only sparse observational networks. This leads to data gaps and limited spatial and temporal data coverage, for example in Siberia, parts of Canada and in mountainous regions (Pallandt et al., 2022). Therefore, an inventory of research sites can aid in the identification of those gaps and provide guidance where new sites should be established.

To support data-driven syntheses and modeling activities with high-quality flux data, and facilitate the training and evaluation of earth system modeling and remote sensing applications, regional eddy covariance networks (AmeriFlux, EuroFlux, AsiaFlux; Baldocchi et al. (2001); Aubinet et al. (1999); Mizoguchi et al. (2009)) and global databases were established (Fluxnet2015, Fluxnet-CH$_4$, SRDB-V5, COSORE; Pastorello et al. (2020); Delwiche et al. (2021); Bond-Lamberty et al. (2020)). Beyond these initiatives, several synthesis efforts that include the high northern latitude domain provide ecosystem or method-specific greenhouse gas data. These include, for example, the Arctic-Boreal CO$_2$ flux database (ABCflux) that combines data from eddy covariance towers and flux chambers for terrestrial ecosystems (Virkkala et al., 2021b), the Boreal–Arctic Wetland and Lake Methane Dataset (BAWLD-CH$_4$) which synthesised chamber-based fluxes (Kuhn et al., 2021), the global lake and reservoir CO$_2$ synthesis for eddy covariance towers (Golub et al., 2023), or the Global River Methane Database (GRiMeDB) involving multiple non-eddy covariance techniques (Stanley et al., 2023).

While existing databases strongly contributed to advancing the understanding of climate change impacts on Arctic ecosystems (Ramage et al., 2024), all of them come with certain limitations with respect to comprehensive coverage. Most importantly, the synthesis efforts and databases listed above are either limited to one observational platform such as eddy covariance towers (Pastorello et al., 2020; Golub et al., 2023) or flux chambers (Jian et al., 2021; Bond-Lamberty et al., 2020; Kuhn et al., 2021), or are confined to single gases, for example carbon dioxide (Virkkala et al., 2021b) or methane (Kuhn et al., 2021). Moreover, important ancillary information including site activity status or data coverage across different seasons is often lacking or difficult to extract from existing repositories, further complicating the tasks of evaluating network coverage and pinpointing gaps therein (Pallandt et al., 2022). Finally, in some cases information in databases is outdated, leading to contradictory metadata between repositories, and some (newer) sites not being listed.

Aiming at comprehensive metadata coverage across greenhouse gas species and platforms at high northern latitudes, we present the structure and the characteristics of a new meta-dataset, ARGO, which is a compilation of metadata for sites where carbon dioxide (CO$_2$), methane (CH$_4$) or nitrous oxide (N$_2$O) have been measured. The focus of this new meta-dataset is to make existing data visible and searchable, and merge information across disciplinary boundaries, while the actual observational

data can be accessed through provided links to related publications and databases. ARGO is therefore restricted to summarising characteristics of sites and datasets, and does not contain the actual data, while providing direct links provide convenient access to the original greenhouse gas data repositories. The five observational platforms considered to monitor greenhouse gas processes include (1) eddy covariance towers and (2) flux chambers, both operated on terrestrial or aquatic ecosystems (Fig. 1) and aiming at resolving processes at local to landscape scales. Furthermore, (3) atmospheric towers and (4) airborne measurements provide atmospheric observations that represent processes at regional to pan-Arctic scales. Finally, the estimation of (5) dissolved gas concentrations monitors highly relevant information that is available mostly for aquatic sites across a distributed Arctic network. ARGO aggregates greenhouse gas metadata specific to Arctic and boreal conditions within the Arctic polar region across these different platforms. To facilitate easy data selection and prompt visualisation, the meta-dataset is presented in an interactive online tool (https://www.bgc-jena.mpg.de/argo/) to provide an openly accessible and comprehensive overview for the research community. Our centralised repository for greenhouse gas metadata will guide future research efforts, ensuring that resources are directed towards filling critical gaps in our understanding of greenhouse gas observations in Arctic and subarctic regions.

2   Methods

2.1   Framework

ARGO comprises metadata of study sites with greenhouse gas measurements from various observational platforms (Fig. 1) at high northern latitudes. The metadata consolidates basic information about location of the sites and their characteristics, measurement period, contact information, and links to scientific publications, published datasets, and repositories (Table 1). Further definitions of compiled data specific to each observational platform are given separately. The full list of parameters included in ARGO for each observational platform are given in Tables A1 to A5. With the help of ARGO, users can easily find out what type of greenhouse gas observations have been conducted where, in which years and by whom, and can address various questions related to high northern research sites. Information on different spatio-temporal and methodological categories is represented in ARGO:

- **Study domain**: This meta-dataset comprises sites within the borders of the Arctic polar region (Meredith et al., 2019), which primarily encompasses the Arctic biome and those parts of the boreal biome that are characterised by cryosphere elements such as permafrost and persistent winter season snow cover. The delineation of the domain has been defined somewhat flexible on purpose, allowing to include also sites further south and outside of this core domain due to their importance for overcoming data gaps for specific regions or biome types.

- **Land cover**: We distinguish the ecosystem type represented by a study site between barren, cropland, forest, grassland, lake, ocean, reservoir, river, shrubland, tundra, urban, and wetland based on available information (from publications or input from site operators and researchers). The lake category includes ponds and puddles, while the river category includes streams, ditches and canals. Where multiple ecosystem types apply to a site, we list all of them.
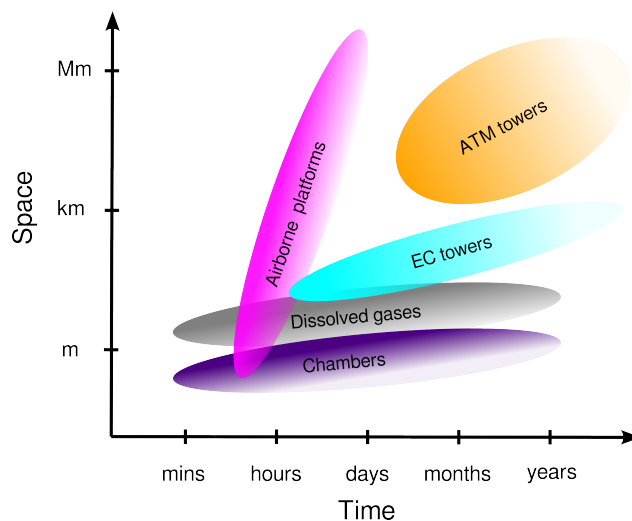
Figure 1. Stommel diagram showcasing temporal and spatial scales of observational platforms.

- **Timeframe**: Observations obtained at a specific location or area of interest studied between 1970 and 2024 were considered for this analysis.

- **Seasonality**: To categorise study periods, we distinguish seasons when measurements were conducted between summer as the period of the growing season (May–October) and winter as the snow- and ice-covered season (November–April). This definition does not necessarily align with the seasonal patterns of the different sites, but is used here for simplicity to differentiate between field visits taking place at different times of the year.

- **Gas species**: The greenhouse gases CO_2, CH_4, and N_2O were considered.

- **Types of measurement**: Greenhouse gas measurements in this context include the assessment of atmospheric mole fractions, as well as vertical ecosystem-atmosphere, soil-atmosphere, or water-atmosphere fluxes, and concentration measurements of greenhouse gases dissolved in water.

2.2 Terrestrial versus aquatic systems

The study sites included in this database comprise a wide range of ecosystem types. We further divided them into two major categories, terrestrial and aquatic systems, because the processes governing greenhouse gas dynamics vary significantly between these systems, as do the potential controls on these variations. Terrestrial systems refer to all land-based observations, for example in forests, grasslands, and wetlands. Aquatic observations depict inland freshwater ecosystems, including lakes, rivers, reservoirs, ponds, streams, and ditches, but exclude ocean-based sites. Given their large footprints that usually comprise mixed landscapes, observational data from atmospheric towers and airborne measurements were not assigned to specific

Table 1. Summary of the main site information in ARGO also shown in the online tool. More extensive tables outlining additional metadata can be found in the appendix. Measurement platforms are abbreviated with EC_Tower (eddy covariance towers), Chamber (chamber-based and ebullition measurements), Dissolved (dissolved gas measurements), ATM_Tower (atmospheric towers), and Airborne (drone- and airplane-based measurements).

Column	Description
Site_Name	Name of the site
Site_ID	Abbreviation of site name, or network code (if applicable)
Latitude	Latitude position of the site (decimal degrees North)
Longitude	Longitude position of the site (decimal degrees East)
Ecosystem	Type of ecosystem of the site
Contact	Name of responsible person of the site
Contact_Email	E-mail address of responsible person
Years	Time period of measurements
Type	Type of observational platform (ATM_Tower, EC_Tower, Chamber, Dissolved, Airborne)
Country	Country of the site
Reference	Full citation of publication (if applicable)
Data_Availability	Link of original database (if available)
Link	Link to data source or repository

105 ecosystems, and for further analysis are assumed to represent terrestrial systems. The remaining platforms have terrestrial or aquatic contributions, or both.

2.3 Observational platforms

ARGO contains metadata from five distinct observational methods which cover the main techniques for in-situ greenhouse gas flux monitoring. Figure 1 displays the spatio-temporal scales associated with each of these platforms. The large range of 110 scales, from minutes to years and from meters to thousands of kilometers, emphasises the need for a dataset that combines the strengths of different observational techniques for supporting comparative studies, data syntheses and modelling efforts.

2.3.1 Atmospheric towers

Sites belonging to this monitoring platform can collect data on atmospheric greenhouse gas mole fractions at regular intervals throughout the year. At most sites, towers are operated over a period of several years to decades. These measurements within 115 the continental boundary layer integrate information from surface-atmosphere fluxes for larger regions, with their footprints often covering areas of several 1000s of km^2, but varying with the sampling height. As such, these data can be used to estimate fluxes when assimilated in atmospheric inverse modeling frameworks.

Measurements include both discrete flask air samples collected in the field and shipped to a laboratory for analysis, and continuous in-situ measurements using gas analysers installed at the sampling location. Typically, discrete air samples are collected in pairs of glass air flasks at weekly intervals, and are analysed for major gases such as CO_2, CH_4, and N_2O, as well as minor trace gases and isotopic signals. Flask-based observations are mainly used to constrain long-term trends, and allow detailed attribution of the origin of air masses, for example, based on isotopic analyses. Continuous in-situ measurements, typically available at hourly time steps, allow more detailed analysis of seasonal and short-term patterns, including variations in diurnal cycles.

Aside from the main site information summarised in Table 1, ARGO consolidates information on tower details, including ground elevation, tower height, and network provider. In addition, the database provides a summary of specific details about the time period of CO_2, CH_4 and N_2O measurements. Information is provided on the sampling methodology, whether conducted in-situ or by flask sampling system, as well as details of the gas analysers and the sampling scheme. Supplementary information on the availability of other measurements, such as carbon monoxide, carbon isotopes, and other greenhouse gases, is incorporated where available.

2.3.2 Eddy covariance towers

The eddy covariance method has been established as a routine tool for measuring gas exchange between the biosphere and the atmosphere since the late 1980s (Baldocchi et al., 1988). The technique is based on high-frequency instruments that continuously sample the turbulent fluctuations in wind speed and gas concentrations in the lower atmospheric boundary layer. After considering certain assumptions, net surface-atmosphere exchange fluxes for the sampled ecosystem can be derived based on the covariance between the vertical wind speed and gas concentration fluctuations.

In most cases, eddy covariance towers are deployed in a stationary setup and are accompanied by a range of ancillary measurements to resolve environmental parameters and local meteorology. Fluxes are commonly aggregated to half-hourly averages corresponding to a specific dynamic footprint, with fetch sizes ranging between a few 100s of meters to a few kilometers depending on the tower height. Deployment times usually exceed one year, so that investigation of diurnal and seasonal cycles is possible, and for longer deployment times inter- and intra-annual variability can be monitored on an ecosystem scale. Due to maintenance and power supply limitations under harsh climate conditions, eddy covariance towers are often not operated in the winter within the Arctic polar region (Pallandt et al., 2022).

The main metadata parameters for the eddy covariance towers are shown in Table 1, and further include information about measurement periods grouped by greenhouse gas (CO_2, CH_4 and N_2O), instrumentation types used for wind and greenhouse gas measurements, and complementary parameters that were measured. In addition, flux contributions from terrestrial and aquatic ecosystems are indicated.

2.3.3 Flux chambers

The chamber method involves the estimation of greenhouse gas fluxes within a sealed sample volume or headspace created with a chamber over soil or water. The concentration changes of gases within the headspace are monitored over time. Fluxes

are estimated based on measured concentration gradients and environmental conditions (temperature, pressure) obtained from direct measurements. Generally, chamber measurements are used to capture instantaneous fluxes on small spatial scales (<1 m², Fig. 1). Approaches range from static chambers to automated systems, whereas static chambers are most common due to their low cost and simple deployment, even though they can only capture episodic snapshots of trace gas fluxes at selected sampling sites. Automated chambers are less common, require more resources and maintenance, but at the same time have the potential to deliver frequently repeated observations over months to decades. In ARGO, we did not differentiate between transparent or opaque chambers.

Apart from chamber measurements, this observational platform includes measurements taken to obtain ebullition fluxes. This pathway of gas release is especially relevant in freshwater environments. Ebullition measurements are typically conducted using bubble traps which consist of inverted funnels that are submerged and capture bursting bubbles rising from the sediment to the surface (Casper et al., 2000; Hamilton et al., 1994). Bubble traps are typically deployed over hours to days and fluxes are derived from volume and gas concentrations of the sampled bubbles. Ebullition fluxes represent a sporadic pathway of gas release and are often assessed simultaneously with chamber measurements.

Site locations for chamber measurements are given as general areas of deployment for simplicity. This means that research areas are listed as sites, even though measurements may occur at many locations at the plot-scale within a specific research area. Metadata for this observational platform include more details about analysis techniques, chamber types used, and measurement periods. Chamber measurements were divided into terrestrial and aquatic measurements. In the latter case, chambers were commonly equipped with floats to avoid submersion.

2.3.4 Dissolved gases

This observational platform comprises measurements derived from analysed water samples, including water surface samples from aquatic sites as well as groundwater samples at terrestrial sites. Typically, dissolved gas concentrations are obtained through either in-situ or laboratory analyses with a greenhouse gas analyser. For some freshwater sites, water-air fluxes are derived from dissolved gas concentrations and the gas transfer velocity following Fick's law. A large number of techniques to derive gas transfer velocities exist and further discussion can be found in the literature (Klaus and Vachon, 2020; Wang et al., 2021).

Dissolved gas concentration measurements can be used to identify vertical surface-atmosphere exchange and lateral transport mechanisms, and particularly the input of carbon and nutrients to aquatic systems from surrounding landscapes or vice versa. Furthermore, fluxes derived from dissolved gas concentrations serve as an additional method in lieu of chamber measurements to determine sources and sinks of greenhouse gases in freshwater ecosystems.

In ARGO, additional information about techniques for sampling and analysis, instrumentation and measurement periods can be found for this observational platform.

2.3.5 Airborne platforms

Airborne observations provide a snapshot of greenhouse gas flux patterns or mole fractions over large areas. Airborne plat-
forms (research manned aircrafts, or unmanned aerial vehicles (UAVs)) are commonly instrumented with flask samplers or
gas analysers to sample greenhouse gases in the atmosphere, supported by a suite of meteorological instrumentation such
as anemometers or temperature sensors. Manned aircrafts, and larger UAVs, hold the capacity to carry eddy-covariance in-
strumentation that can directly measure surface-atmosphere fluxes, while particularly for smaller UAVs the limited payload
mostly allows to sample mole fractions of greenhouse gases in the lower atmosphere. In the latter case, surface fluxes can
be constrained based on vertical and horizontal patterns in greenhouse gas mole fractions, or mass balance approaches when
sampling, for example, the upwind and downwind sections of defined control volumes over the study area.

The resulting gas measurements from airborne platforms are typically campaign-based and not repeated as regularly over
extended periods of time. Airborne platforms are therefore highly suitable to complement stationary measurement platforms
such as eddy covariance towers and chambers that provide high quality flux data though only for a fixed research area with
limited spatial extent. Episodic airborne campaigns can overcome scaling challenges, and allow to assess the representativeness
of stationary measurement devices located in heterogeneous terrain.

With ARGO, we provide details about the measurement unit, number of flights conducted during campaigns, and ancil-
lary measurements. For simplicity, we do not provide exact flight paths, but rather the outer bounds of areas covered during
campaigns.

2.4 Data collection

The collection process covered a wide range of data sources. The version of the meta-dataset presented herein represents the
status in June 2024. Metadata for eddy covariance sites were gathered predominantly from different flux databases (Fluxnet,
AmeriFlux, AsiaFlux, ICOS, and NEON; Table 2) as described previously (Pallandt et al., 2022). Besides, metadata for at-
mospheric towers and airborne observations were gathered from various networks led by different institutions (NOAA, ICOS,
JR-STATION, ECCC, GAW, ORNL DAAC, and HALO DB; Table 2). In addition, metadata embedded in existing synthe-
ses (Virkkala et al., 2018; Virkkala and Miska, 2018; Virkkala et al., 2021b; Kuhn et al., 2021; Stanley et al., 2023; Golub
et al., 2023) were integrated or were extracted from scientific publications. The search for chamber and dissolved gas mea-
surements was carried out in Google Scholar, Web of Science, ResearchGate, and eLibrary. Publications were searched using
the following keywords: "carbon", "carbon dioxide", "methane", "CO2", "CH4", "greenhouse gas", "flux", "concentration",
"dissolved", "Arctic", "permafrost", "tundra", "forest-tundra", "wetland", "lake", "pond", "river", "waterbody", and "reservoir".
Furthermore, personal communication with site operators and researchers aided in the search for sites.

Table 2. Overview of general data sources for the different observational platforms of ARGO with descriptions and links to websites.

Name	Observational Platforms	Description	Link
Fluxnet	Eddy covariance towers	Eddy covariance network (global)	https://fluxnet.org/
AmeriFlux	Eddy covariance towers	Eddy covariance network (Americas)	https://ameriflux.lbl.gov/
AsiaFlux	Eddy covariance towers	Eddy covariance network (Asia)	https://www.asiaflux.net/
ICOS	Eddy covariance towers, Atmospheric towers	European Integrated Carbon Observation System	https://www.icos-cp.eu
NEON	Eddy covariance towers, Atmospheric towers	National Ecological Observation Network in United States of America	https://www.neonscience.org/data
ABCflux	Flux chambers	Synthesis of arctic-boreal CO_2 fluxes	https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1934
BAWLD-CH_4	Flux chambers	Synthesis of boreal-arctic wetland and lake CH_4 fluxes	https://arcticdata.io/catalog/view/doi:10.18739/A2DN3ZX1R
GRiMeDB	Dissolved gases, Flux chambers	Synthesis of global river carbon fluxes and concentrations	https://portal.edirepository.org/nis/mapbrowse?packageid=knb-lter-ntl.420.2
ECCC	Atmospheric towers	Atmospheric tower observation network by Environment and Climate Change Canada	https://www.canada.ca/en/environment-climate-change.html
GAW	Atmospheric towers	Global Atmosphere Watch Programme of World Meteorological Organization	https://community.wmo.int/en/activity-areas/gaw
NOAA/GML	Atmospheric towers	Global Atmospheric tower observation network by National Oceanic and Atmospheric Administration/Global Monitoring Laboratory	https://gml.noaa.gov
JR-STATION	Atmospheric towers	Japan–Russia Siberian Tall Tower Inland Observation Network by National Institute for Environmental Studies	https://www.cger.nies.go.jp/en/climate/pj1/tower/
ORNL DAAC	Airborne platforms	Oak Ridge National Laboratory Distributed Active Archive Center for Biogeochemical Dynamics	https://daac.ornl.gov/get_data/
HALO DB	Airborne platforms	Halo Database for Airborne Data	https://halo-db.pa.op.dlr.de/

3 Metadata overview

ARGO comprises metadata of sites with greenhouse gas measurements from five observational platforms (atmospheric and eddy covariance towers, chambers, dissolved gases, and airborne measurements) across the high northern latitudes gathered between 1970 to 2024 (Fig. 2). With the focus of the meta-dataset being placed on the Arctic polar region, about 84 % of sites are located above 60° N, and 52 % above the Arctic Circle. With almost 95 % of sites, the vast majority of the data stems from countries with land inside the Arctic Circle, including USA (32 %), Russia (26 %), Canada (20 %) and Fennoscandian nations (16 %). The total latitudinal range of sites spans 42–83° N, with the southernmost sites being dominated by atmospheric towers with footprints extending over 1000s of km, and thus still covering large areas of the Arctic polar region. As mentioned above, the delineation of the ARGO domain was kept flexible to allow filling gaps with data from more southerly locations, leading to data contributions also from Estonia, Iceland, Ireland, Mongolia, Kazakhstan or Poland.

The temporal development of site coverage across monitoring networks is summarised in Fig. 3. After a slow start in network development following the establishment of the first monitoring sites in the 1970s to 1990s, the coverage of active greenhouse gas measurement sites within the Arctic polar region increased rapidly in the 2000s (Fig. 3). Until present, the network continues to grow, with the stagnation or even decrease in active site counts shown in Fig. 3 for the most recent years being an artifact associated with delays in the processing the collected data and publishing it in databases and research articles. With regards to the activity of sites during different seasons of the year, two-thirds of the sites or studies investigated greenhouse gases exclusively during the growing season (eddy covariance: 73 %; chambers: 73 %; dissolved: 61 %; airborne: 100 %). At the same time, only about 30 % of the included sites are currently listed as being active year-round or during the winter months (eddy covariance: 27 %; chambers: 19 %; dissolved: 36 %; airborne: 0 %). All atmospheric towers are listed as operational year-round. The remaining minority of sites was investigated during various times of the year, or no information on the timing of site activity was available.

The distribution of different ecosystems within ARGO is shown in Fig. 4. Lakes and rivers are well represented, especially for chamber-based and dissolved gas measurements. Tundra and wetlands are the most common terrestrial sites for chamber-based measurements. Forests and wetlands are most commonly targeted by the eddy covariance tower network.

The meta-dataset covers a comprehensive set of 62 atmospheric towers, almost 250 eddy covariance towers (regardless of operation time), and fourteen individual campaigns for airborne measurements. More than 1000 data points are listed for flux chamber measurements, close to 900 data points of dissolved greenhouse gases, with varying contributions from terrestrial and aquatic ecosystems (Fig. 5). ARGO is based on a research community of more than 400 scientists and provides their contact details (email address or links to datasets and websites, Table 1) where available. Three-quarters of the data are linked to 490 individual published studies, while the remaining data are either published in the form of datasets only or remain unpublished to date.
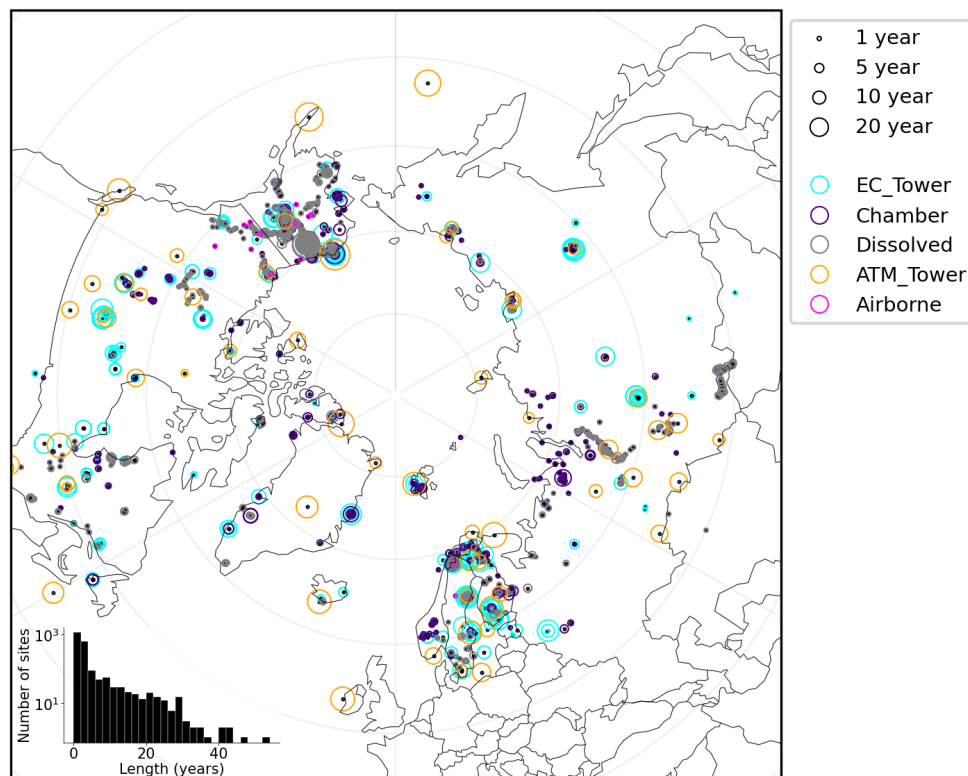
Figure 2. Distribution of study sites within the research domain. Colors of the circles represent sites for each observational platform included in the present database. For airborne measurements, the mean latitude and longitude of the outer bounds are shown. The size of the circles represents the number of years with measurements. The histogram at the bottom left shows the number of all sites binned in number of years with measurements. Measurement platforms are abbreviated as stated in Table 1.

4 Online mapping tool

The ARGO meta-dataset is visualised and made accessible online in the form of a map-based search tool (https://www.bgc-jena.mpg.de/argo/), offering an interactive map with site locations divided by observational platform. The conception of the online meta-database was strongly supported by two workshops held at the Arctic Data Center in Santa Barbara, CA, in 2018 (Parmentier et al., 2019), and with an ongoing data search the ARGO meta-database will be updated regularly. With the online tool, users can explore the database, filter metadata by observational platform, select measurement years, latitude and longitude zonal bands, terrestrial or aquatic ecosystem data, and greenhouse gases (CO_2, CH_4, N_2O). Additionally, users have the option to filter the metadata by country or seasonal activity. These filter options provide the user with a convenient tool to survey measurement sites and available datasets for various study purposes in the Arctic polar region. Selected variables are shown in a summary table (Table 1) providing key information for each site.
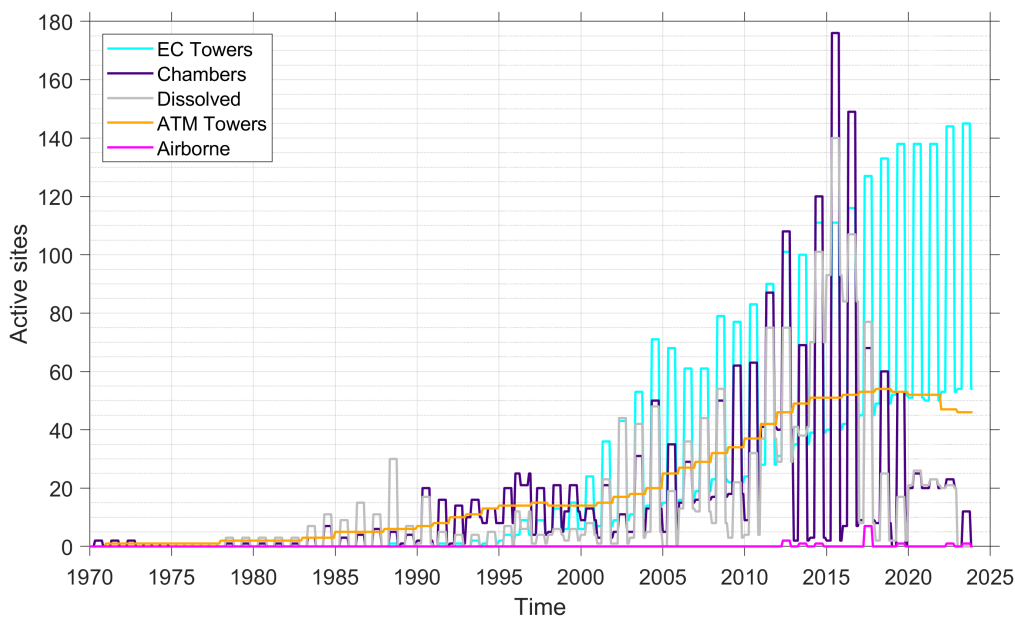
Figure 3. Cumulative temporal coverage of all available sites/studies shown separately for each observational platform. Measurement platforms are abbreviated as stated in Table 1. Please note that for EC and ATM towers, sites are considered to be operational until discontinuation is indicated by the operators, therefore data coverage remains high for these categories also in recent years. For all other categories, data availability relies on results or data being published, therefore time lags between measurement and being listed in this database lead to declining data coverage for the past decade. A distinction is made between summer and winter activity. In cases where seasonal activity data are not available, only summer activity is assumed, except for atmospheric towers which are assumed to be active throughout the year.

For enhanced user accessibility, the metadata for all observational platforms along with a readme file is available for download in the form of compressed comma-separated files. Furthermore, users can download specific metadata tailored to their selected variables using the provided filters. Where relevant greenhouse gas flux or concentration data are publicly available, a link to the repository or dataset is provided within the meta-database. In case data remains unpublished, contact details are listed to initiate direct communication with members of the research community responsible for the site-specific data.

The meta-database also offers a "How to Use" page, providing a detailed description of the web page functionalities and instructions on how users could use the application. Furthermore, the "About" page provides comprehensive information regarding the scientific foundation of this project, including guidelines on citing the meta-database, references, and details about funding and the authors involved.

5   Data quality

To acquire comprehensive site-level metadata, and extend information provided by online databases, we conducted online surveys among principal investigators of Arctic flux sites, asking for information on, for example, exact times of measurements,

Figure 4. Counts of ecosystem types within the database. Note that ecosystem types are only given for eddy covariance towers, chamber-based, and dissolved gas measurements. Atmospheric tower footprints and airborne measurements are assumed to cover too large of an area for this analysis.

instrumentation details, or ancillary measurements complementing the flux data (Pallandt et al., 2022). Moreover, principal
265 investigators have been prompted to inform us about changes in site status. These surveys provide a direct link between site
operators or researchers and the meta-data provided in ARGO, therefore the submitted data were assumed to be accurate based
on the participant's expertise. In addition, the metadata collection relied on existing peer-reviewed syntheses and published
datasets. Since the metadata is visualised online, verification of the collected data by the involved network of researchers was
possible in the past and continues to be easily possible.

270 To avoid displaying outdated information, the meta-database will be regularly checked and updated by the authors of this
study in collaboration with site operators and researchers. The authors highly encourage site operators and researchers using
the database to contact us with information, for example, about new sites, or updates regarding existing sites.
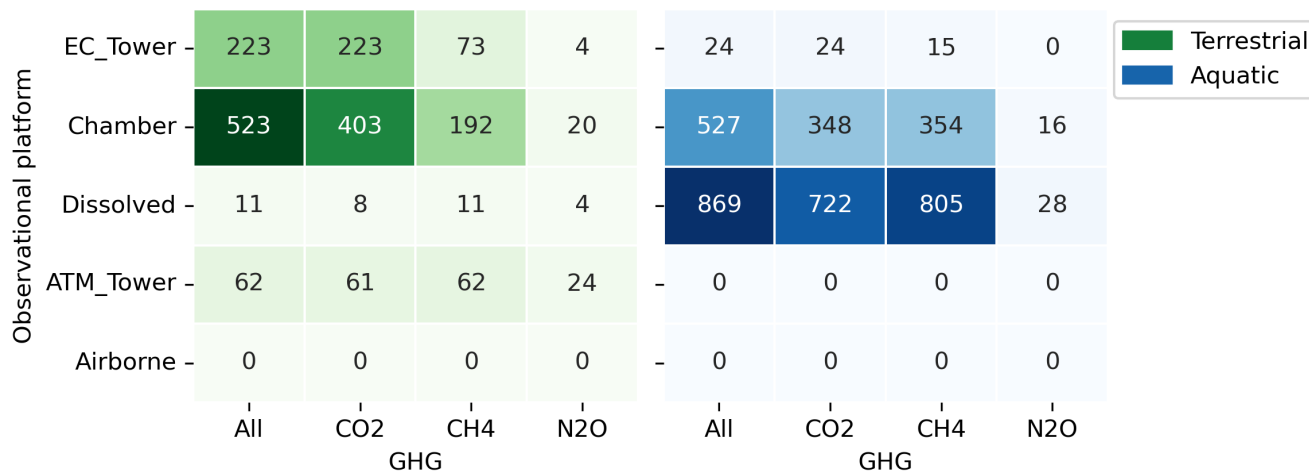
Figure 5. Number of sites for each observational platform and measured greenhouse gas (GHG) divided into terrestrial and aquatic sites. Measurement platforms are abbreviated as stated in Table 1.

6 Data gaps and limitations

Site locations are given as coordinates (latitude and longitude) with varying accuracy since sites were occasionally not geo-
referenced especially in earlier studies, so that coordinates were approximated. In other cases, measurements repeated at close-by locations were consolidated into one single location to assure data usability and manageability within ARGO. This should be considered when high accuracy of site locations is required, for example, for merging in-situ observation with gridded remote sensing products.

The distribution of sites was visualised using ecoregions as defined by Olson et al. (2001) (Fig. 6). While the analysis identified well-represented ecoregions for CO_2, CH_4, and N_2O measurements in western Scandinavia and northern and central Alaska, significant data gaps persist in other regions such as parts of Russia (eastern Siberia) or Canada (south of Hudson Bay). This is illustrated by the difference in average site density across large regions: Alaska showcases 52.06 sites per 100,000 km^2, while Eastern Russia lags behind with only 1.95 sites per 100,000 km^2. The distribution of sites separated by observational platform are shown in Figures A1 to A3.

More specific data gaps identified by ARGO include, for example:

- **N_2O measurements**: With only 93 data points, N_2O is the least covered greenhouse gas within ARGO, and substantial temporal and spatial gaps still need to be filled: Outside the atmospheric tower network (24 towers), more than 50 % of the available N_2O data are provided by sites in Fennoscandia, leading to a strong regional focus, and large gaps in most other Arctic regions. Finally, less than 5 % of the data cover the cold season.

290   – **Airborne observations**: Same as for N_2O, only few datasets are available, and these are unevenly distributed. From the 14 airborne datasets currently listed in ARGO, just one is not focusing on Alaska and Northwestern Canada, and no campaigns were conducted during wintertime.

    – **Off-season methane**: For methane, terrestrial measurements are largely restricted to the growing season, and excluding the atmospheric towers, the database currently just lists 49 entries for year-round or wintertime datasets. This gap is

295   partly balanced by a quite large number (292) of wintertime dissolved gas measurements; however, these are mostly coming from experiments focusing on small regions in Alaska and Russia.

The current trend of relocating research activities operated by Western scientists from Russian research sites to other regions as a result of ongoing conflicts between Russia and Ukraine further degrades the number of active sites in Russia, with significant impacts on Arctic science overall (López-Blanco et al., 2024; Schuur et al., 2024).
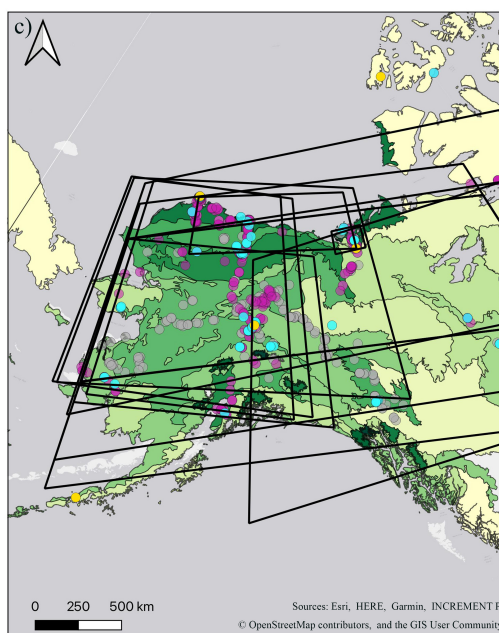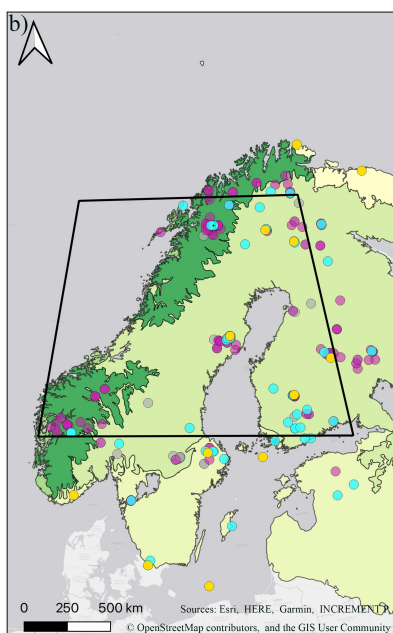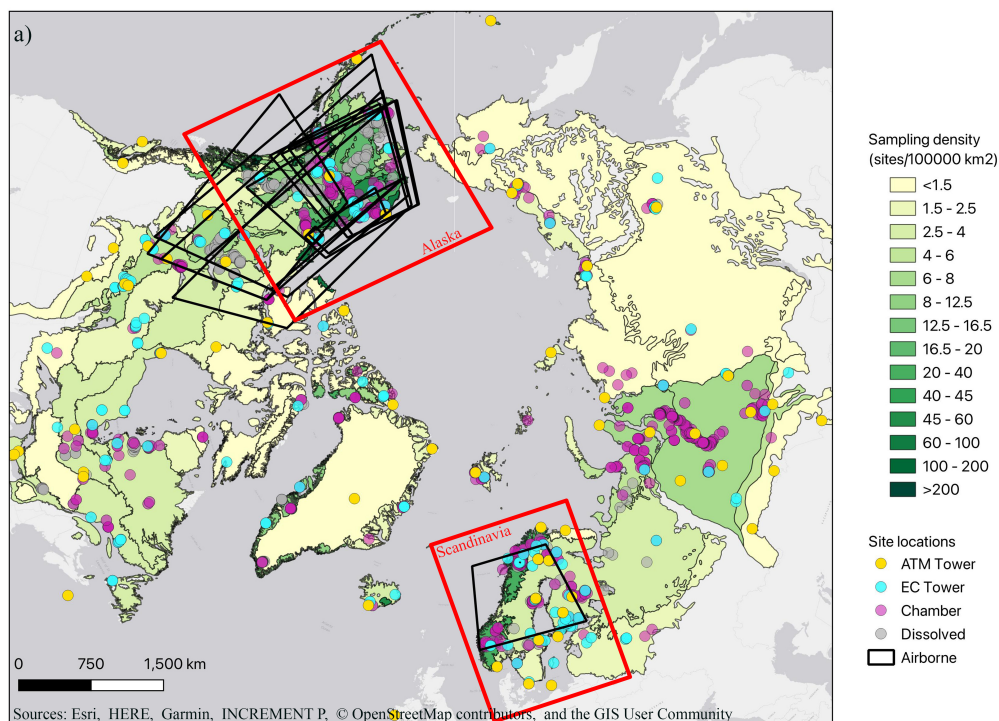
Figure 6. Density of study sites within ecoregions across high northern latitudes (a), with zoomed view for Scandinavia (b), and Alaska (c). Numbers are normalised to ecoregion area. Ecoregions were defined based on Olson et al. (2001). Measurement platforms are abbreviated as stated in Table 1.

7   Data availability

The ARGO metadata version 1 presented in this study has been published to the Zenodo repository (https://doi.org/
10.5281/zenodo.13870390) under license CC-BY-4.0 (Vogt et al., 2024). The interactive tool visualising the latest version
of the metadata can be accessed online (https://www.bgc-jena.mpg.de/argo/), and metadata download is also facilitated from
that platform.

8   Code availability

The code to reproduce the online tool can be found in a public GitLab repository (https://git.bgc-jena.mpg.de/ipas/argo) and at
https://doi.org/10.5281/zenodo.12795381.

9   Conclusions

The novel meta-database ARGO comprises information on temporal and spatial extent as well as technical and ancillary
information on five different observational platforms that provide information on greenhouse gas processes within the Arctic-
boreal domain. The metadata within ARGO can be used as a base to support the planning and execution of studies aiming at
synthesising functional relationships governing greenhouse gas exchange processes, and aggregating greenhouse gas budgets,
at the pan-Arctic scale or across selected sub-regions. In this context, ARGO aims at expediting the search for existing data,
and maximising the available database, for ongoing and future synergy studies. In addition, the ARGO meta-database provides
an easy-to-use tool to visualise data coverage and identify gaps therein, therefore guiding future research activities towards
strengthening observational capacities by filling crucial data gaps.

As data scarcity remains a major obstacle to data-driven assessments of carbon budgets in this study domain, improving
visibility and access to distributed and heterogeneous data sources will reduce discrepancies in observation-based carbon
budget estimates between synergy studies. ARGO metadata will be continuously updated as new sites and studies become
available. The online mapping tool ensures that metadata is visible to interested users, and facilitates the selection of data by
applying filters.

ARGO supports the Arctic-boreal research community to better understand greenhouse gas cycle processes in the northern
study domain, which is highly important for assessments of global greenhouse gas dynamics and future climate projections.

Appendix A: Metadata descriptors

A full list of parameters contained in the ARGO metadata is presented in Tables A1 to A5. Since each observational platform
has slightly different parameters, the descriptors are given in separate tables. The spatial distribution of study sites for each
observational platform are given in Figures A1 to A3.

Table A1. Full list of metadata descriptors for atmospheric towers.

Column	Description
Type	Type of observational platform (here ATM_Tower for atmospheric towers)
Site_Name	Name of the site
Site_ID	Abbreviation of site name (as used in data repositories)
Latitude	Latitude of the site (in decimal degrees North)
Longitude	Longitude of the site (in decimal degrees East)
Country	Country of the site
Contact	Name of person responsible for site/data
Contact_Email	E-mail address of responsible person
Data_Availability	Link to data source or repository (if available)
Additional_Information	Link to additional information, e.g. description about the tower
Ground_Elevation	Elevation of sample collection above ground (m)
Tower_Height	Height of measurement tower above ground (m)
Network_Provider	Provider of the data
Gas_Analyser	Information on instrument used for gas analysis
Insitu_Parameters	List of gases sampled in-situ
Flask_Parameters	List of parameters analysed from flask sample
Sampling_Scheme	Methodological details about sampling frequency
GHG	Greenhouse gases measured: CO_2 (carbon dioxide), CH_4 (methane), N_2O (nitrous oxide)
Start_CO2	First year of CO_2 measurements
End_CO2	Last year of CO_2 measurements
Start_CH4	First year of CH_4 measurements
End_CH4	Last year of CH_4 measurements
Start_N2O	First year of N_2O measurements
End_N2O	Last year of N_2O measurements
Season_Activity	Measurement period of the year
Terrestrial	Flag for land-based observations/fluxes
Aquatic	Flag for inland freshwater observations/fluxes

Table A2. Full list of metadata descriptors for eddy covariance towers.

Column	Description
Type	Type of observational platform (here EC_Tower for eddy covariance towers)
Site_Name	Name of the site
Site_ID	Abbreviation of site name (as used in data repositories)
Latitude	Latitude of the site (in decimal degrees North)
Longitude	Longitude of the site (in decimal degrees East)
Country	Country of the site
Contact	Name of person responsible for site/data
Contact_Email	E-mail address of responsible person
Data_Availability	Link to data source or repository (if available)
Reference	Full citation of publication (if applicable)
Reference_Short	Short citation of publication (if applicable)
Additional_Information	Link to additional information, e.g. description about the tower
Anemometer	Anemometer model (if available)
Gas_Analyser	Information on instrument used for gas analysis
Power	Type of power source
Ecosystem	List of ecosystems applicable to the site: barren, cropland, forest, grassland, lake, ocean, reservoir, river, shrubland, tundra, urban, wetland
GHG	Greenhouse gases measured: CO_2 (carbon dioxide), CH_4 (methane), N_2O (nitrous oxide)
Complementary_Measurements	List of other variables measured
Start_CO$_2$	First year of CO_2 measurements
End_CO$_2$	Last year of CO_2 measurements
Start_CH4	First year of CH_4 measurements
End_CH4	Last year of CH_4 measurements
Start_N2O	First year of N_2O measurements
End_N2O	Last year of N_2O measurements
Season_Activity	Measurement period of the year
Terrestrial	Flag for land-based observations/fluxes
Aquatic	Flag for inland freshwater observations/fluxes

Table A3. Full list of metadata descriptors for flux chambers.

Column	Description
Type	Type of observational platform (here Chamber for chamber-based and ebullition measurements)
Site_Name	Name of the site
Latitude	Latitude of the site (in decimal degrees North)
Longitude	Longitude of the site (in decimal degrees East)
Country	Country of the site
Contact	Name of person responsible for site/data
Contact_Email	E-mail address of responsible person
Data_Availability	Link to data source or repository (if available)
Reference	Full citation of publication (if applicable)
Reference_Short	Short citation of publication (if applicable)
Analysis_Technique	Sample analysis: In-situ or Lab (ex-situ laboratory-based analysis)
Gas_Analyser	Information on instrument used for gas analysis
Chamber_Type	Type of chamber: Manual chamber, Automatic chamber, or Ebullition trap
Ecosystem	List of ecosystems applicable to the site: barren, cropland, forest, grassland, lake, ocean, reservoir, river, shrubland, tundra, urban, wetland
Ecosystem_Details	Description of ecosystem of the site
GHG	Greenhouse gases measured: CO_2 (carbon dioxide), CH_4 (methane), N_2O (nitrous oxide)
Start_Year	First year of measurements
End_Year	Last year of measurements
Season_Activity	Measurement period of the year
Terrestrial	Flag for land-based observations/fluxes
Aquatic	Flag for inland freshwater observations/fluxes
Comment	Notes and comments

Table A4. Full list of metadata descriptors for dissolved gases.

Column	Description
Type	Type of observational platform (here Dissolved for water-based gas concentration measurements)
Site_Name	Name of the site
Latitude	Latitude of the site (in decimal degrees North)
Longitude	Longitude of the site (in decimal degrees East)
Country	Country of the site
Contact	Name of person responsible for site/data
Contact_Email	E-mail address of responsible person
Data_Availability	Link to data source or repository (if available)
Reference	Full citation of publication (if applicable)
Reference_Short	Short citation of publication (if applicable)
Ecosystem	List of ecosystems applicable to the site: barren, cropland, forest, grassland, lake, ocean, reservoir, river, shrubland, tundra, urban, wetland
Ecosystem_Details	Description of ecosystem of the site
GHG	Greenhouse gases measured: CO_2 (carbon dioxide), CH_4 (methane), N_2O (nitrous oxide)
Start_Year	First year of measurements
End_Year	Last year of measurements
Season_Activity	Measurement period of the year
Terrestrial	Flag for land-based observations/fluxes
Aquatic	Flag for inland freshwater observations/fluxes
Comment	Notes and comments

Table A5. Full list of metadata descriptors for airborne platforms.

Column	Description
Type	Type of observational platform (here Airborne)
Site_Name	Name of the site
Latitude	Northern latitude of the overflown area (decimal degrees North)
Latitude_S	Southern latitude of the overflown area (decimal degrees North)
Longitude	Western longitude of the overflown area (decimal degrees East)
Longitude_E	Eastern longitude of the overflown area (decimal degrees East)
Country	Country of the site
Contact	Name of person responsible for site/data
Contact_Email	E-mail address of responsible person
Data_Availability	Link to data source or repository (if available)
Reference	Full citation of publication (if applicable)
Reference_Short	Short citation of publication (if applicable)
Number_Of_Flights	Number of flights per campaign
Complementary_Measurements	List of other variables measured
Measurement_Unit	Type of measurement unit (aircraft or unmanned aerial vehicle)
GHG	Greenhouse gases measured: CO_2 (carbon dioxide), CH_4 (methane), N_2O (nitrous oxide)
Campaign_Start	First day of measurements
Campaign_End	Last day of measurements
Season_Activity	Measurement period of the year
Terrestrial	Flag for land-based observations/fluxes
Aquatic	Flag for inland freshwater observations/fluxes
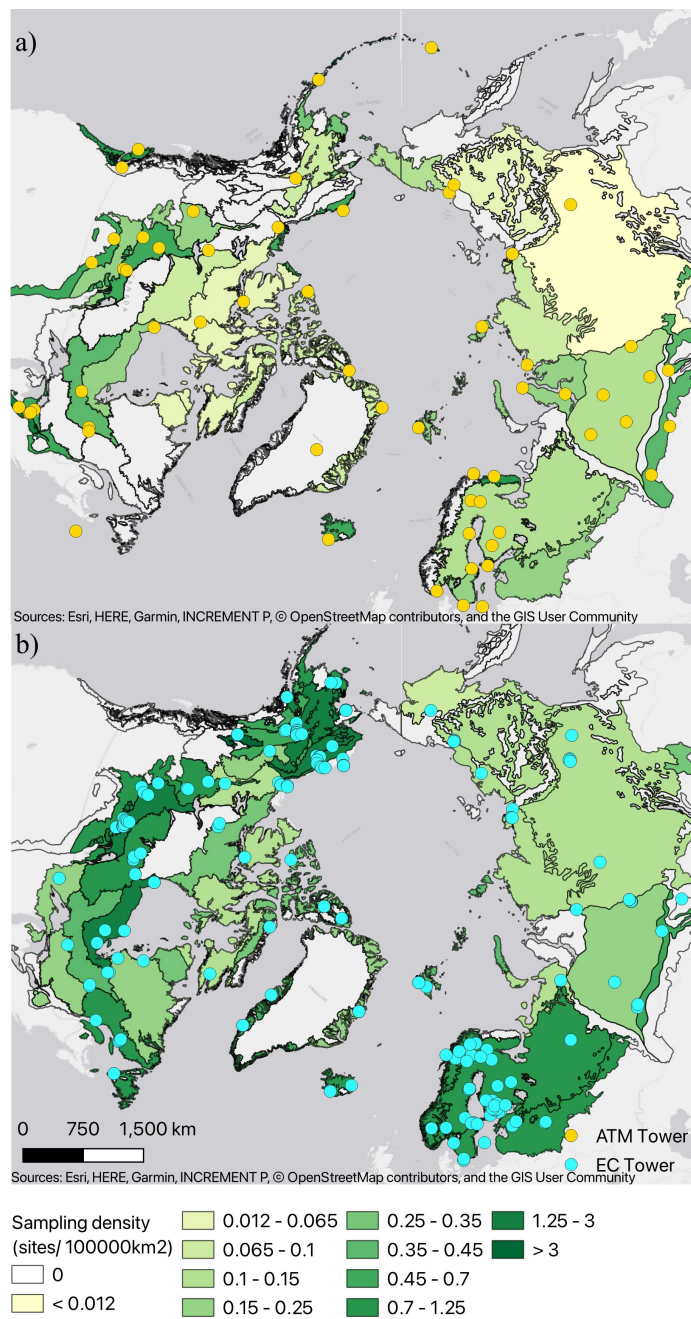
Figure A1. Density of study sites for atmospheric towers (a) and eddy covariance towers (b) within ecoregions across high northern latitudes. Numbers are normalised to ecoregion area. Ecoregions were defined based on Olson et al. (2001).
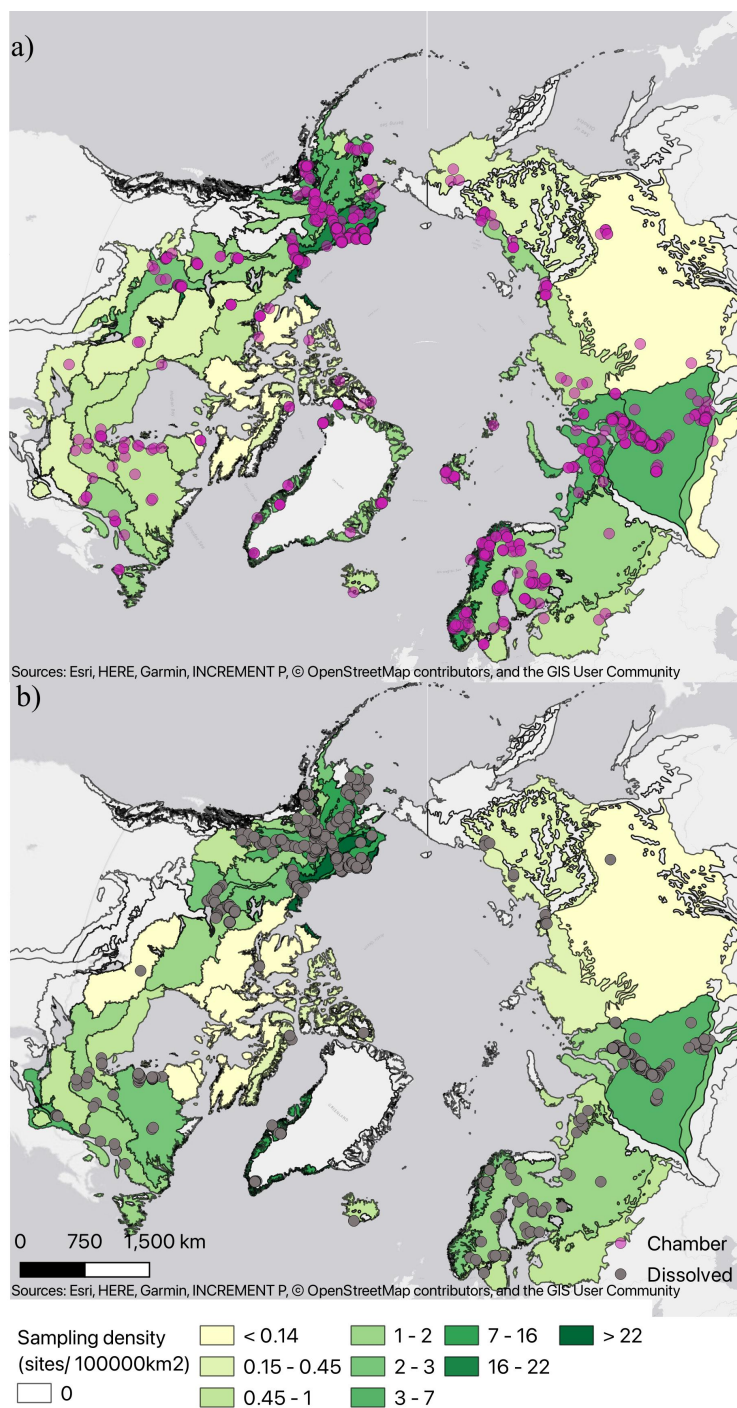
Figure A2. Density of study sites for flux chambers (a) and dissolved gases (b) within ecoregions across high northern latitudes. Numbers are normalised to ecoregion area. Ecoregions were defined based on Olson et al. (2001).
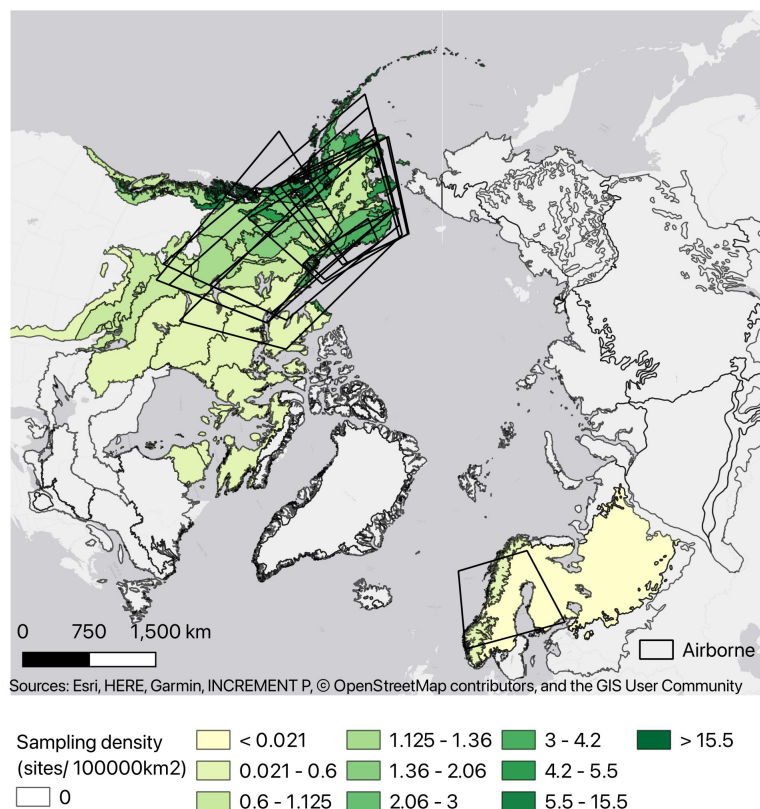
Figure A3. Density of study sites for airborne platforms within ecoregions across high northern latitudes. Numbers are normalised to ecoregion area. Ecoregions were defined based on Olson et al. (2001).

Author contributions. MMTAP, GC, EAGS, and MG conceived the original version of the online mapping tool. JV, MMTAP, LSB, AB, KI, MK, MM, GC, KA, AMV, and IW contributed to data provision. Data were jointly curated by JV, MMTAP, LSB, AB, KI, MS, MM, GC, and AMV. The formal analysis was conducted by JV, MMTAP, LSB, AB, KI, MS, and AMV, with EAGS, and MG responsible for funding acquisition and supervision. Software was developed and maintained by MMTAP, MS, and GC, while JV, MMTAP, KI, and MS contributed to data visualisation. JV, LSB, AB, KI, and MG wrote the original manuscript. All authors reviewed the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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