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Arctic observations and sustainable development goals – Contributions and examples from ERA-PLANET iCUPE data

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ABSTRACT

Integrative and Comprehensive Understanding on Polar Environments (iCUPE) project developed 24 novel datasets utilizing in-situ observational capacities within the Arctic or remote sensing observations from ground or from space. The datasets covered atmospheric, cryospheric, marine, and terrestrial domains. This paper connects the iCUPE datasets to United Nations' Sustainable Development Goals and showcases the use of selected datasets as knowledge provision services for policy- and decision-making actions. Inclusion of indigenous and societal knowledge into the data processing pipelines enables a feedback mechanism that facilitates data driven public services.

1. Introduction

Climate warming occurs at the fastest pace in Arctic regions, leading to drastic changes in environmental and socio-economic systems in high latitudes. The Arctic regions are facing wide ranging challenges linked with globalization, exploitation of natural resources, increasing economic activity, new shipping routes, and demographic changes (Lappalainen et al., 2016). Loss of sea ice opens up for access to natural resources, allows increased extraction of resources, and year-round accessible shipping routes, increasing anthropogenic activities and impacts in the region (Farré et al., 2014). Warming driven thaw of permafrost areas leads to changes in land cover, landslides, surface stability and emissions of greenhouse gases and mobilization of pollutants, such as mercury and persistent organic pollutants (POPs).

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Permafrost, glacier ice sheet melting, and water discharge is changing terrestrial and aquatic ecosystems, atmospheric pollution and pollutant mobilization impacts food safety and human health locally and globally (e.g. AMAP, 2003, 2015, 2021; Arnold et al., 2016; IPCC, 2021).

Recently, sustainable development goals (SDGs), as set by the United Nations (UN), have been discussed in an Arctic focus (Ganapin, 2018). The SDGs address the dual challenge of overcoming poverty and protecting our planet. They reflect a comprehensive vision of sustainable development that covers economic, social, and environmental dimensions. It is now recognized that the usual geographic subdivisions, like north and south, tropics and Arctic, no longer apply. Rather, the UN recognizes the critical role the Arctic plays in global climate change, biodiversity, and pollution cycling. Aligning the diverse perspectives and interests of Arctic peoples and humans elsewhere will require global governance. The SDGs will need to provide a framework that stimulates and supports all-inclusive sustainable decision-making.

Regarding the historical development of SDGs, rooting back to the 1980s and approaching the next reporting in 2023, the SGD framework is based on scientific data and observations, the definition of indicators that allow to formulate targets and finally the goals. The SGD framework is built as a pyramid, a large increasing base of available data and scientific developments and narrowing to achieve the 17 declared SDGs as focused goals. The framework includes the Essential Variables (EVs), a concept that appeared in the 1990s in context of the Global Climate Observing System (GCOS) and enabled groups of linked variables that critically characterize the state of a complex system under observation (Houghton et al., 2012). This inclusion of EVs into the SDG structural framework aims to streamline the use of observations towards indicators and to make the policy driven indicators independent from the observational platforms, allowing more flexibility on both structural levels (Reyes et al., 2017).

Sustaining Arctic Observing Networks (SAON) recently introduced the framework of Shared Arctic Variables (SAV, Murray et al., 2020). This action focuses on selected, very impactful essential variables through a co-design process that are widely beneficial rather than generating an extensive list of variables. This allows us to incorporate diverse perspectives, knowledge and data contributors, such as the recent MOSAIC expedition or World Meteorological Organization's (WMO) World Weather Research Programme (WWRP) together with the World Climate Research Programme (WCRP), that enable us to expand observational capacities in the Arctic (Eicken et al., 2021). However, the identification, development and refinement of Essential Variables and Shared Arctic Variables require multi-domain observational platforms and associated data streams (e.g. Weatherhead et al., 2018; Starkweather et al., 2022; Petäjä et al., 2020). This will facilitate monitoring development towards a sustainable Arctic (Kulmala et al., 2021).

In the framework of Arctic observations and sustainable development goals, the aim of this work is to summarize data pilots that link selected Arctic datasets to potential end users. The users have multiple interests in the Arctic region that range from local communities to globally operating entities like the Group of Earth Observations (GEO), GCOS, UN, and the European Commission. In more detail, we map the required data streams that support EVs and SDGs that act as a framework to steer climate mitigation relevant decisions and allow adapting and monitoring the progress of the measures particularly in the Arctic region.

2. iCUPE datasets

Within the Horizon-2020 ERA-PLANET programme, the iCUPE project (Integrative and Comprehensive Understanding on Polar Environments; https://www.atm.helsinki.fi/icupe, Petäjä et al., 2020) is focused on Arctic observations that include large scale remote sensing Earth Observations (EO) and in-situ data. While EO data with Arctic perspective are available via large national and international consortia, the data coverage of in-situ observations is sparser (e.g. Lappalainen et al., 2016). Although several circumpolar long-term observation sites provide atmospheric composition data in the Arctic (e.g. Uttal et al., 2016; Skov et al., 2020; Pernov et al., 2021), quite often the observations are performed during short-term campaigns and expeditions due to economical and logistical reasons. New data is becoming available by long-term actions, such as World Meteorological Organization's Global Atmospheric Watch (WMO-GAW, Laj et al., 2020) and via European Research Infrastructures (International Carbon Observation System (ICOS; https://www.icos-cp.eu), the Aerosol, Clouds and Trace Gases Research Infrastructure (ACTRIS; http://www.actris.net)), or research programs such as the Pan-Eurasian EXperiment (PEEX; https://www.atm.helsinki.fi/peex, Lappalainen et al., 2021), and Global SMEAR (https://www.atm.helsinki.fi/globalsmear), Arctic Monitoring Assessment Program (AMAP; https://www.amap.no), Global Observation System for Mercury (GOS4M; http://www.gos4m.org). In the following sections we showcase the novel Arctic datasets (https://www.atm.helsinki.fi/icupe/index.php/datasets/delivered-datasets) developed in the iCUPE project and showcase how they can be utilized in responding to SDGs in the Arctic.

iCUPE planned and developed more than 20 datasets (DS) during the lifetime of the project. Additionally, four datasets are contributed by Russian partners through the PEEX collaboration network. See Fig. 2 for a representation of iCUPE datasets and their links to EVs.

The development of DS as a process was conceptualized in iCUPE stepwise, backed by a data management plan, and can be used as a general guideline for mobilizing data towards decision processes. In the project planning phase, the scientific work was divided into thematic work packages and associated tasks with the aim of delivering completely novel or aggregated data products from existing long-term observations. At the start of the process, each team working on the DS provided so-called data teasers, a one-page summary of the anticipated DS. The document included contact details of the team working on the DS as well as relevant references to earlier works. Quite often a photo of the person or of the team was included, which brought up into the attention the researchers responsible for the DS. These DS were stored in the project webpage. In the following steps, the DS teasers were utilized to attract and identify potential data users and engage a dialog with users and stakeholders. Once the DS was finalized, a link to it was placed at the iCUPE webpage. At the end of the process, each of the DS (or a link to the DS, if the data volume becomes an issue) was submitted to an openly accessible repository. In iCUPE, Zenodo or other suitable open platform for long-term availability of the DSs and providing them persistent identifiers in line with the FAIR data principles was used.

The iCUPE DS cover a wide and diverse range of topics from pollutants and contaminants that are transported into and/or locally produced by increasing human activities in the Arctic regions, like mercury, black carbon, organic and inorganic aerosols, to parameters such as precipitation in the high latitudes, spatio-temporal dynamics of glacier lakes on the Greenland ice sheet, remotely sensed changes in the Arctic environment, such as changes in sea ice or snow spectral properties, to aspects of urban development in the Arctic leading to changes in local microclimate and urban heat island developments.

To link the iCUPE DS (Table 1) to possible services that deliver EVs and contribute to SDGs we found it beneficial to categorize them. Unfortunately, this step opens multiple possibilities to group the DSs because almost all the data available from Arctic regions can contribute to a suite of relevant SDGs. We tackled this issue by grouping the DSs according to the spatial location of the EVs of interest. Separating by geographical locations in the marine, terrestrial, cryospheric and atmospheric domains is another way to tackle this task. This is applicable to EO, in-situ or model generated datasets. To allow a more detailed categorization we introduced "sample domains" that utilize a "physical location", i.e., where the samples originated from. We used snow, water, and ice cores that are very tangible but also atmosphere, ice sheet, and land cover which are more generalized and abstract, or wider ranging, physical locations (Fig. 2).

Table 1
List of the iCUPE datasets linked to EVs and services to respond to SGDs and potential SDG indicators. Avoiding repetition indicators will be listed once and apply to all rows.

iCUPE Datasets	Linking to SDGs	Potential SDG indicators
Aerosol physical and optical characteristics including equivalent black carbon at Ny-Alesund, Svalbard (*with 3 datasets for aerosol ultrafine particle size distribution, aerosol large particle size distribution, scattering, absorption*)	13, 3, 4	3.9.1, 3.9.2, 3.9.3, 4.7.1, 13.1.2, 13.1.3, 13.2.1, 13.2.2
Anthropogenic contaminants from polar regions (*with 2 datasets for ice cores and snow*)	13, 3, 4	
Arctic atmospheric mercury observations (*with 2 datasets for Hg(0) isotope and Hg(II)*)	13, 3, 4, 14, 15, 17	14.2.1, 14.4.1, 15.3.1, 17.7.1, 17.14.1, 17.18.1
Artificial light sources in the Yamal Peninsula, Western Siberia	13, 3, 4, 11, 17	11.3.2
Blueprint for novel proxy variables integrating in-situ and satellite remote sensing data (*with 2 datasets on condensation sink and mixing layer height*)	13, 3, 4	
Emerging organic contaminants from the Arctic (*with 3 datasets for air, snow, and water*)	13, 3, 4, 14, 17	14.1.1
Fractional snow cover area in selected sites of Svalbard islands, Norway	13, 14, 15	
Ground-validation of precipitation measurements in high-latitudes	13, 4	
Long-term monitoring of gaseous elementary mercury in background air at the polar station Amderma, Russian Arctic	13, 3, 4, 14, 15	
Near-Real-Time aerosol absorption measurements from Zeppelin Station, Ny Ålesund, Svalbard	13, 3, 4	
Organic aerosols in the Arctic	13, 3, 4	
Small-scale vertical and horizontal variability of the atmospheric boundary layer aerosol using unmanned aerial systems	13, 3, 4	
Snow spectral reflectance measurements at Ny-Alesund, Svalbard	13, 4	
Time-series of lakes' size changes in Northeast Greenland	13, 9, 4, 17, 6, 7	6.3.1, 6.6.1, 6.b.1, 7.1.1, 7.2.1, 9.3.1, 9.5.1, 9.5.2
Validated aerosol vertical profiles from ground-based and satellite observations above selected sites (*with 2 datasets for Finland and Siberia)*	13, 3, 4	
Vertical profiles of equivalent black carbon in the Arctic boundary layer at Ny-Ålesund, Svalbard	13, 3, 4	
Visible Near Infrared airborne and simulated EnMAP satellite hyperspectral imagery of Toolik Lake, Alaska	13, 14, 15, 6, 4	

The spatial representation within the iCUPE DSs is presented in Fig. 1. While the most sampling points are located in the Arctic and within the Arctic circle, some measurements were taken in the Antarctic (not shown in figure) and some in Scandinavia and Siberia, including places south of the Arctic circle, at 66.33°N. Justification for this is that the Earth's atmospheric and riverine transport of matter and energy links mid-latitude emissions and run-off to the Arctic region (see Section 3.2).

3. Results and discussion

3.1. Scientific context of selected iCUPE DSs and possible implications to policy

3.1.1. Role of permafrost in the Arctic and global mercury cycle

Within iCUPE we developed several DS on mercury concentrations in the Arctic. Mercury (Hg) levels in the Arctic marine biota are among the highest globally and affect Arctic wildlife and indigenous populations that rely on seafood (AMAP, 2021, 2015, 2011). The relatively few anthropogenic Hg point sources in the Arctic cannot explain the high biota Hg levels. Anthropogenic elemental mercury (Hg^0) originating from industrialized mid-latitude countries has been estimated to have a long atmospheric lifetime (~1 year) and was recognized as a likely source for Arctic Hg (AMAP, 1997; AMAP/UN Environment, 2019; Steffen et al., 2008). In the following years, fast atmospheric Hg^0 oxidation, conversion to reactive Hg^{II} species and massive deposition were reported during springtime (Schroeder et al., 1998) and it was shown that a very large fraction (> 70–80%) of the deposited Hg was photochemically reemitted back into the atmosphere only hours after deposition (Brooks et al., 2006; AMAP, 2011; AMAP/UN Environment, 2019), putting into question its direct impact on biota. A model study suggested that river discharge into the Arctic Ocean (AO) is a source of Hg to biota (Fisher et al., 2012), Russian rivers alone account for about 80% of run-off to the AO.

Recently iCUPE and Arctic GRO studies provided observations on seasonal Russian river Hg fluxes, narrowing down previous estimates in the range of 8–108 Mg y^{-1} to more robust numbers of 37 Mg y^{-1}, 44 ± 4 M y^{-1} (Sonke et al., 2018; Zolkos et al., 2020). Together with estimates of coastal erosion of permafrost soils, releasing 30 Mg y^{-1}, it has become clear that terrestrial Hg inputs are of similar magnitude as atmospheric Hg deposition to the AO, estimated at 76–108 Mg y^{-1} (Dastoor and Durnford, 2014; Soerensen et al., 2016). Recent permafrost soil Hg studies filled data-gaps and were able to associate changes in the Pan-Arctic soil Hg budget with Arctic warming (Olson et al., 2018; Schuster et al., 2018). New iCUPE Hg and carbon data for six soil cores along a 1700 km permafrost gradient in the western Siberian lowlands constrained the pan-Arctic soil Hg budget to 72,000 Mg for 0–30 cm layer depth (Lim et al., 2020). Warming induced changes in permafrost active layer depth may mobilize sufficient Hg to dramatically impact Hg inputs to wetlands and AO.

In the marine environment, a small fraction of inorganic Hg is converted to toxic methylmercury (MeHg), mostly through microbial biotransformation processes. After uptake in freshwater and marine food webs, MeHg can biomagnify to toxic levels in top predators, including humans. So, the risk posed by Hg pollution in Arctic ecosystems is thus not only controlled by the amounts of inorganic Hg transported into the system and cycling within the Arctic environment, but also to what extent the pool of Hg is methylated and accumulated. The 2011 AMAP report on Hg in the Arctic included an extensive discussion of the processes leading to environmental MeHg exposure (AMAP, 2015, 2011; AMAP/UN Environment, 2019). MeHg toxicity considered in risk assessment studies includes neurotoxicity to fetus and children, and cardiovascular risk in adults (Farina et al., 2011; Roman et al., 2011). Moreover, river Hg and marine biota MeHg levels will be important EVs to monitor the impact of Arctic region related SDGs. The datasets provided by iCUPE imply, that beside national emission control policies the efforts on reducing global warming are pivotal to reach lower Hg and MeHg levels in the Arctic, especially as our data show that atmospheric and terrestrial inputs are of similar magnitude.

3.1.2. Persistent organic pollutants and black carbon in the snow – atmosphere interface

In the iCUPE project we prepared datasets covering pollutants in the atmosphere, their transport, and their concentrations in snow. The snowpack is often the recipient of pollutants through dry or wet

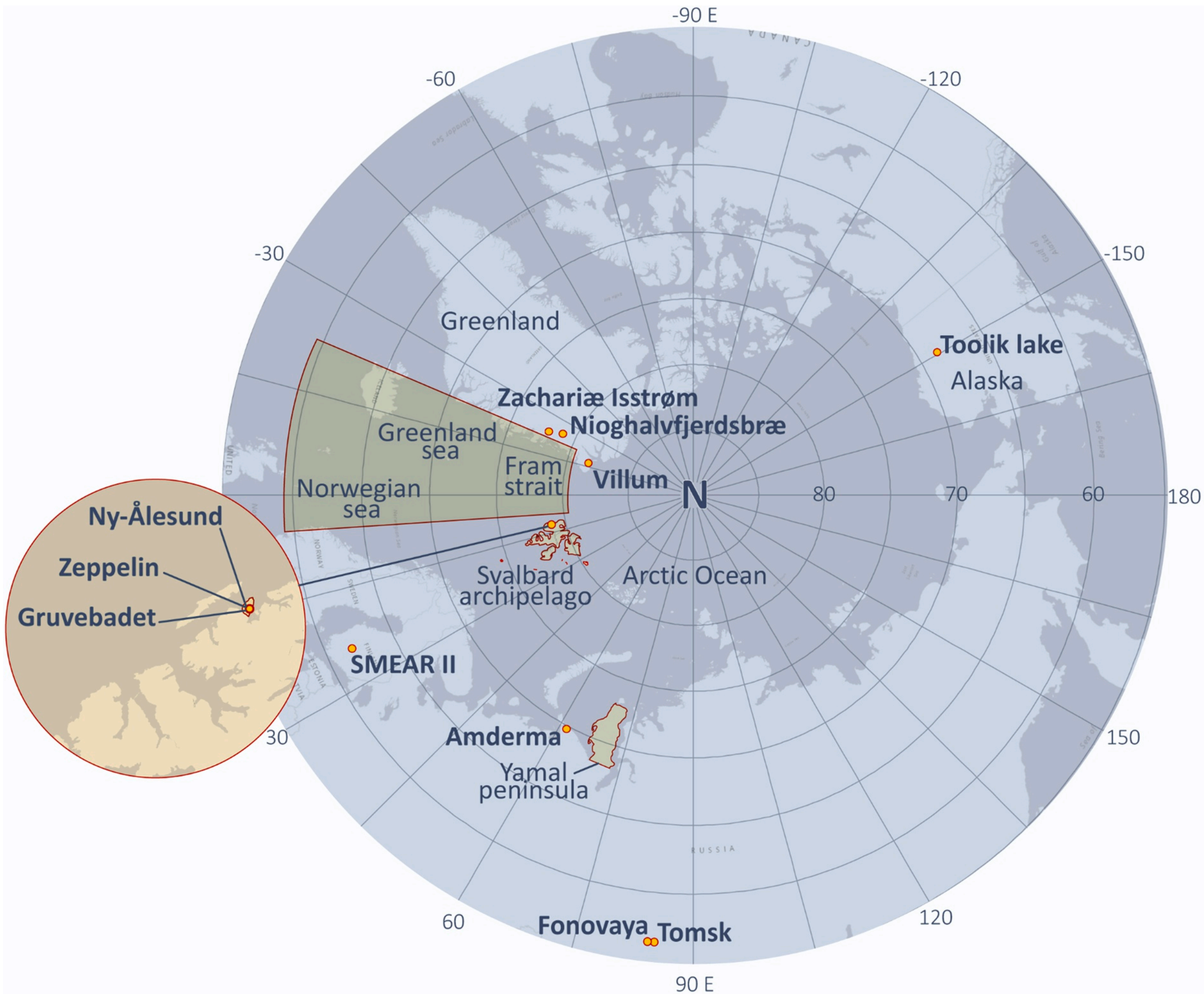

Fig. 1. Spatial coverage of the Arctic iCUPE datasets. The observation methods include in-situ atmospheric, water, snow and ice sampling, ground-based remote sensing and satellite observations.

deposition processes occurred during long-range transport. Depending on solubility, such pollutants can concentrate during the melt season increasing its relative concentration per volume unit. This concentration increase is valid for e.g., black carbon (BC). Many organic compounds are produced naturally, but mankind has developed and introduced an enormous array of new compounds into the environment, all of which can reach the polar regions in both the Northern and Southern hemispheres. It has been suggested that human activity really began to change the environment at the beginning of the 19th century (Crutzen and Stoermer, 2000) with the introduction and use of the steam engine. But a major part of human influence on the global environment occurred during the "Great Acceleration" after 1950s (Lewis and Maslin, 2015) which is identified as "a major expansion in human population, large changes in natural processes, and the development of novel materials from minerals to plastics and the presence of Persistent Organic Pollutants (POPs)". The presence of POPs such as Polycyclic Aromatic Hydrocarbons (PAHs; Gabrieli et al., 2010), Brominated Flame Retardants (BFRs; Bossi et al., 2008, 2016; Hermanson et al., 2010; Vorkamp et al., 2015), Organochlorine and Organophosphate Pesticides (OCPs, OPPs; Bossi et al., 2013; Isaksson et al., 2003) in Arctic ice cores, are clear markers of human activity, and simply show how far these compounds can travel and thus how widely these compounds can be dispersed in the environment and highlight their remanence.

Next to the ocean, snow is the second largest interface between the atmosphere and Earth's surface during winter. Snow deposited on land or ice surfaces is thermodynamically unstable and is in constant evolution through snow metamorphism, which is controlled by temperature gradients in the snowpack. Deposition and release from the annual snowpack are an important part in the cycle of anthropogenic compounds. Because both the changes in snow and ice compositions and the presence of radiation absorbing particles have impact on the surface temperature, these compounds influence the timing of the melting processes which has a strong impact on SDGs in the Arctic context.

Most of the POPs present in the Arctic (and Antarctic environment) are transported there mainly by long-range transport from the lower latitudes except for local pollution caused by the few human settlements and their activities. POPs can be scavenged from the atmosphere during precipitation events and transferred to the environment. In the case of liquid precipitation, frequently during the Arctic summer season, POPs can be deposited onto the glacier surface or above the ground. But the presence of liquid water tends to remobilize the POPs and remove them from the primary deposition areas. During the snow season, we can identify their presence with some degree of accuracy, since during the periods from October until May, snow precipitation continuously accumulates and forms the annual snow cover.

The formation of the annual snowpack is due to continuous snowfall deposition. This snowfall can transfer many impurities, including POPs and BC present in the atmosphere to the snowpack (Vecchiato et al., 2018). During the winter the annual snowpack can become a net sink and a reservoir for many pollutants. While snowpack formation occurs between 6 and 9 months in the Arctic region (depending on the geographical location of a site), the snow melt is occurred at much faster

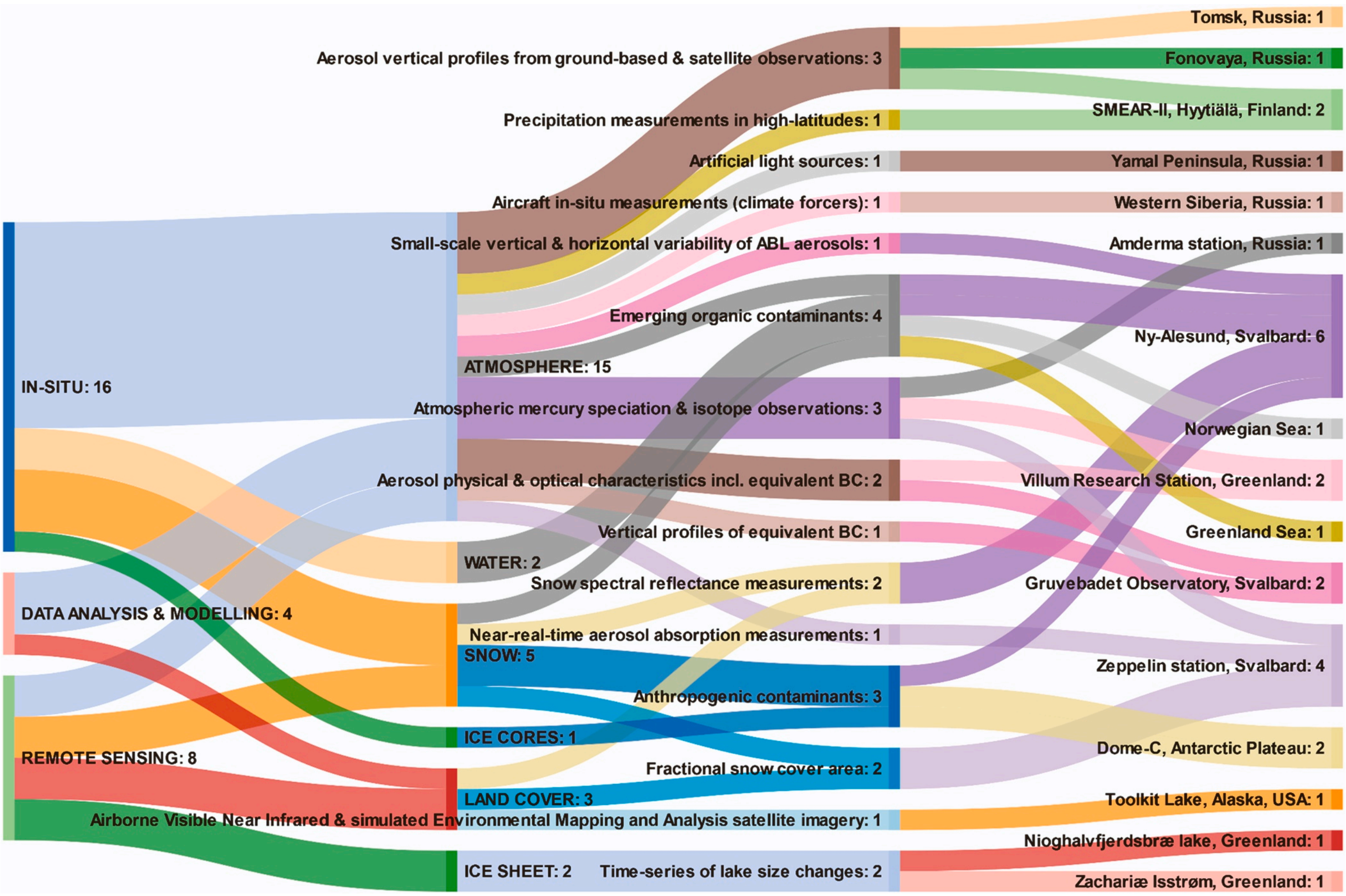

Fig. 2. List of the iCUPE datasets linked to EVs and services to respond to SGDs. The numbers denote how many "items" belong to the category visualized. From left to right, the technical domain (in-situ, remote sensing, modeling) splits into the sample domains, which lead to the datasets and finally is linked to the geographical location where the data was measured.

rate. During the melting season the impurities based on their chemical nature present in the annual snowpack can be released in much shorter periods and cause a "pulse" of these pollutants to the surrounding environment such as the permafrost, glacier streams and lakes (Meyer et al., 2009). Snowpack melting can induce an unquantified and poorly understood amplification of concentrations of e.g., POPs (Casal et al., 2019). The annual snow cover can then change from a sink to a source of pollutants in the spring when it is able to release large amounts of these accumulated compounds again to the environment. The release of these compounds can be retained and accumulate in the upper permafrost layer and affect the local flora as well the fauna, especially herbivores (Hung et al., 2010).

The deposition of BC on snow and ice-covered surfaces has been estimated to be a major climate forcer within the Arctic environment (Quinn et al., 2008, 2014). BC deposition can either happen by wet deposition via precipitation as aged BC particles are involved in cloud formation because of their changing character from hydrophobic (during emission) to hydrophilic (transformation during transport) particles or via dry deposition. BC is not expected to be released during the melt season, but rather more will accumulate and up-concentrate in the snowpack enhancing snow melt process.

Another important atmospheric component affecting surface albedo is the deposition of dust material that is released from non-snow-covered surfaces in Arctic areas and delivered by long range transport from mid- and low latitudes. Within a changing Arctic climate with increasing temperatures, more snow-free surfaces are available releasing larger amounts of soil dust via events with higher wind speeds. Such transported and locally emitted dust pollution can be transported to other Arctic locations and deposited on snow- and ice-covered surfaces changing albedo drastically as soil dust can be of strongly light-absorbing character. This complex feedback mechanism has not been quantified yet but has been discussed in the latest AMAP report (AMAP, 2021) on short-lived climate forcers (SLFCs) as a general topic of high importance. Therefore, the extension of atmospheric dust measurements and the set-up of a corresponding network in the Arctic had been recommended.

In the light of the major path by atmospheric transport, local regulations and policies to reduce contaminant and BC emission outside the Arctic are effective actions towards reduced deposition on the snow and ice surfaces. In terms of locally emitted dust that will increase with increasing human activity in the Arctic, like ore-mining as an example, also local regulations need to be put into place.

3.1.3. Atmospheric pollutants (aerosol particles and selected trace gases)

Within iCUPE, a set of atmospheric pollutant concentration datasets were developed and delivered. Atmospheric pollutants including aerosols and trace gases have multiple effects on the environment. The SLCFs, notably black carbon (BC), tropospheric ozone (O_3) and methane (CH_4) warm the Earth's climate whilst aerosols such as sulfate cool the climate. Aerosols and tropospheric O_3 are also harmful to human health and pollutant deposition has deleterious effects on ecosystems. Long-term observations of atmospheric pollutants at surface sites provide important information about seasonal and long-term trends which are needed to monitor pollutant responses to increasing anthropogenic emissions or decreases resulting from emission mitigation. Daily or hourly O_3 or particulate matter $PM_{2.5}$ (aerosol concentrations less than 2.5 μm) data are used to study pollution episodes and their effects on human health. Satellite data give a picture about the spatial pattern of pollutants such as $PM_{2.5}$ or O_3 precursors such as carbon monoxide (CO) or nitrogen oxides (NO_x) over emission regions as well as long-range transport from source regions into the Arctic. Data from airborne campaigns provide more detailed snapshots of the vertical distribution profiles of aerosols and trace gases in the boundary layer as well as in the free troposphere. These datasets are used to validate pollutant emissions and quantify processes influencing the transformation of pollutants as they are transported away from emission regions. The latter is important for improved model predictions of climate impacts and assessment of pollutant deposition on ecosystems.

Emissions related to oil and gas extraction in northern Russia have been identified as important sources of BC (Stohl et al., 2013) and CH_4 (Ialongo et al., 2021). Gas flaring activities contribute significantly to Arctic BC but there are considerable uncertainties in emission estimates from this source and other emissions in this region. For example, BC emission estimates in 2010 from flaring, residential and industrial sectors in the Arctic BC emissions (Huang et al., 2015) are higher (224 kT yr^{-1}) than in ECLIPSE.v5 (170 kT yr^{-1}) (Klimont et al., 2017). Differences are also apparent in CH_4 emission estimates over Siberia for anthropogenic and natural wetland emissions. Effects of BC deposition onto Arctic surfaces, especially on snow and ice are triggering changes in the freezing and melting cycles and impact directly on different SDGs, especially those linked to clean water, food, and health but as well those linked with local economic developments which in the Arctic are strongly linked to snow cover and ice stability.

Due to Arctic warming precursor emissions responsible for the formation of new particles are expected to be enhanced, thus leading to a changed aerosol population (Dall'Osto et al., 2018) impacting Arctic climate directly by scattering and absorbing solar radiation and indirectly by altering the available number of cloud condensation nuclei (CCN) needed for cloud formation. This feedback mechanism might be significant for future Arctic climate considerations related to the fact that availability of CCN for cloud formation in Arctic regions is generally relatively limited. While atmospheric pollutants are the most fugitive with global impact because of the atmospheric transport their regulation needs to cover national and international policies.

3.2. Integrating observations and models

Integration and synthesis of comprehensive multi-platform observations and modeling results was one of the focuses of iCUPE (Petäjä et al., 2020). This work provided several comprehensive datasets in the Arctic and facilitated a step in the use of such data towards EVs by creating a new level of data products including multiple sources. To improve assessment of climate and environmental impacts of SLCFs an integrated approach has been developed as part of iCUPE which is illustrated in Fig. 3. An integrated analysis of in-situ and satellite data combined with prior modeling is used to identify emission sectors influencing observations, discrepancies in emission inventories and to refine emission estimates. This leads to improvements in integrated models which include detailed treatments of SLCFs, and which are the tools used to assess SLCF climate impacts. It may also inform the need for improved observation strategies to monitor and assess SLCFs and their response to emission mitigation.

For example, analysis of pollution plumes sampled by the YAK-AEROSIB aircraft (Paris et al., 2010) over gas flaring regions in northern Russia, together with use of VIIRS night-light satellite data to identify flaring regions and source-receptor modeling, have been used to identify discrepancies in BC emission inventories, including identification of regions where emissions are missing in these inventories (Petäjä et al., 2020; Onishi et al., 2021). The analysis shows that discrepancies between observed BC and detailed atmospheric chemical-aerosol-transport model simulations can be partly explained by inconsistencies in emission datasets or missing emissions. Since the gas flaring sector is targeted for emission mitigation by the Arctic Council additional observations in this region are highly recommended (AMAP, 2021). The framework allows for iterative improvement in the emission inventories and to implement an adaptive policy process that relies on regularly and timely updated integrated data and EVs.

In order to improve our understanding of Arctic pollution and its impacts, and to enhance availability of timely information to the public and to policy- and decision-makers through GEO and Copernicus, integrated methodologies adapted to the specificities of the Arctic challenges are required that can operate a smart convergence of data streams of in-situ and satellite measurements. Such approaches will require

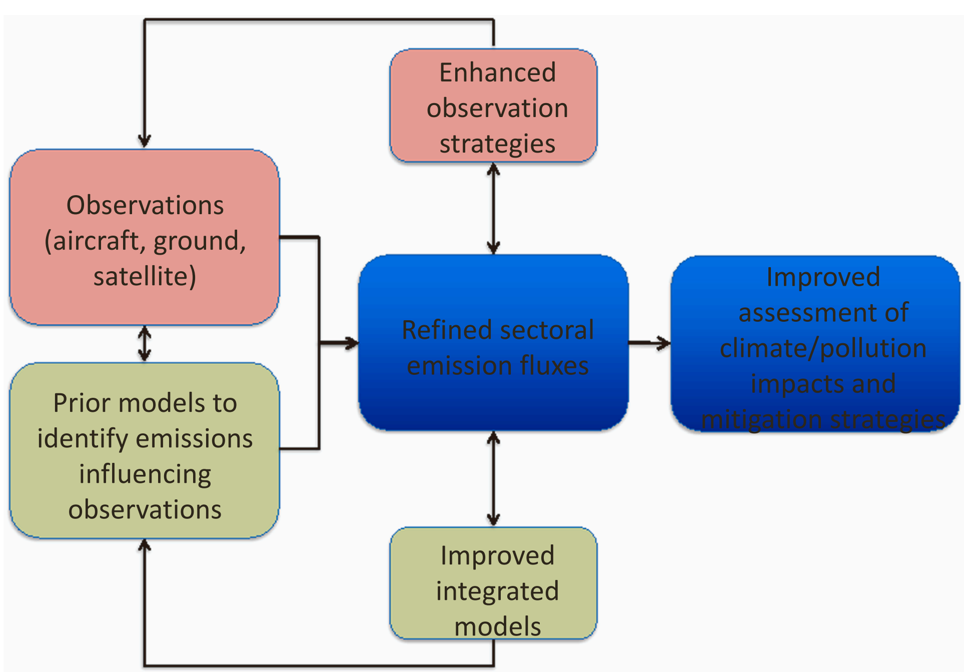

Fig. 3. A data-model integration scheme that enables iterative improvement of observational capacities in the Arctic and to build proxies and EVs used to improve the data flow contributing towards SDGs.

enhanced data processing and analysis capability, satellite validation capability for the Arctic, as well as robust Earth System Models (ESM) and assimilation approaches such as the one outlined here. Synthesis of data from different sources was the key in developing integrative iCUPE datasets enabling improved environmental assessment of Arctic pollutants.

Integrated observations and the use of models is an essential building block in the mobilization of data and research towards science-based knowledge creation. The GEO discovery and access broker (GEO-DAB) and DIAS (Data and Information Access Services) systems allow to portray this knowledge further towards the public and policy makers. Especially in the process of science-based decision making and iterative regulation policies on e.g., emission reductions or pollutant controls this step is of pivotal importance.

3.3. Contextualization of selected iCUPE datasets and their links to SDGs

In a schematic manner, the context of iCUPE datasets as part of the global chain of data streams supporting decision making and enabling monitoring the pathway towards the SDGs is shown in Fig. 4. As a practical example we can take atmospheric pollution (SDG 3: Clean Air, Health) in the Arctic which is linked to public health and well-being. The sources of Arctic air pollution consist of local sources within the Arctic and long-range transport from remote sources of the hemispheric domain around the Arctic (Arnold et al., 2016). Boreal wildfires emit BC that impacts Arctic warming (SDG 13: Climate Action), but also sub-Arctic permafrost carbon and mercury release that is microbially and abiotically emitted as CH_4, CO_2 and Hg^0 from Arctic wetlands (SDG 15: Life on land) and the Arctic Ocean (SDG 14: Life below water) into the atmosphere (Serikova et al., 2019; Sonke et al., 2018; Schaefer et al., 2020).

Continuing with the atmospheric pollution example, the transported pollution will be deposited on the Arctic surfaces. As shown in Fig. 4, POPs and other deposited pollution can be released from the annual snowpack and then enter to the Arctic food chain affecting the herbivores and carnivores at the top of this food chain. The annual snow cover might not only be a physical barrier or interface between the ground and the atmosphere in polar regions, but also act as a component of the environment able to affect, with its seasonal dynamics, the release of pollutants and the health of the Polar terrestrial fauna (SDG 15).

In addition, the release of snow melt water as a "pulse" at the end of the snow season could influence the coastal environment where the main water discharges are likely to occur. Compounds and pollutants not retained directly by the terrestrial ecosystems can be discharged into the surface coastal waters and possibly affect life underwater (SDG 14). Several POPs are hydrophobic and tend to be absorbed onto suspended particles, but they can also be taken up by aquatic species and can undergo biomagnification process before or after biotransformation

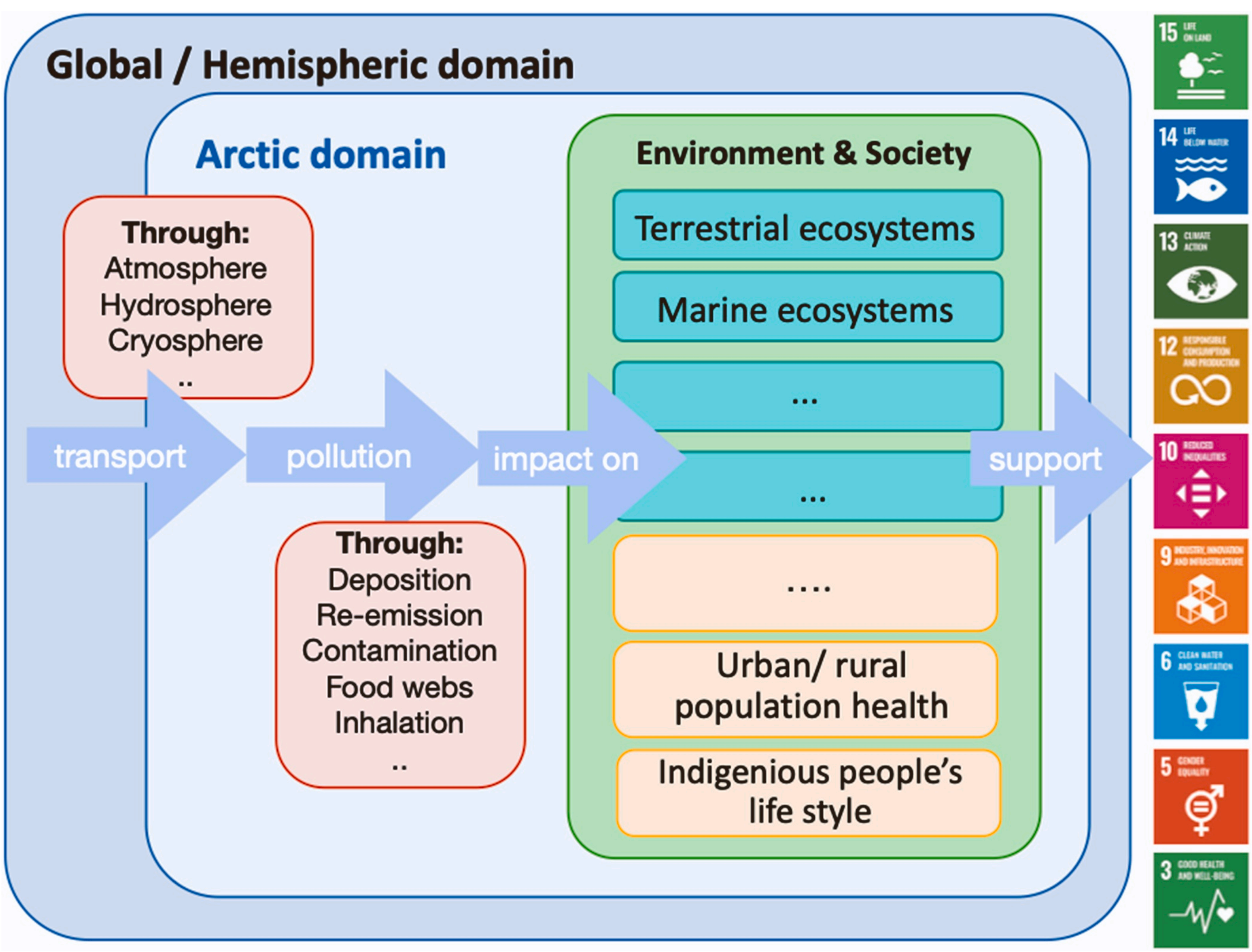

Fig. 4. Pollutants in the Arctic are either local or transported from lower latitudes. The transport routes include atmospheric, marine and cryospheric pathways. The pollutants are deposited, re-emitted, processed and accumulated into the food webs. This has impacts on the Essential Variables related to environment and safety of different ecological or thematic domains, such as marine ecosystems, population health and indigenous lifestyle. This data can be used to monitor routes towards sustainability with the help of SDGs.

processes.

From this perspective, the role of pollution may need in future a more comprehensive view, taking storage of pollutants by snow accumulation on ice sheets and glaciers in the Arctic into account. These pollutants will be released by two mechanisms. At first, they are contained in icebergs that are dispatched from tidewater glaciers in the Arctic, drifting and melting in fjords and currents around the ice sheets and ice caps. At second, the melting at the surface of glaciers and ice sheets leads to percolation of melt water and thus leading to further vertical transport, but moreover surface run-off, supraglacial lake formation and drainage, is leading to massive discharge in pulses into the ocean and ice marginal lakes (Schröder et al., 2020). As the number of ice marginal lakes around Greenland is increasing (Carrivick and Quincey, 2014) and floods (Carrivick et al., 2017) arising from such lakes show peaks in release of pollutants into rivers feeding the ocean (Søndergaard et al., 2015), there are many implications arising of importance for local communities, as well as food webs.

Forecasting and projecting future release of pollutants is of interest for a few SDGs, such as 6, 13 and 14. Moreover, melting and mass loss of the Greenland ice sheet is opening opportunities for economic growth, but comes with challenges. To foster sustainable development in the Arctic a combined approach of simulations, satellite remote sensing and monitoring stations in the field is the most promising approach. A combination of ice sheet modeling (Rückamp et al., 2018, 2020) combined with hydrology models (Beyer et al., 2018), is what is needed on the simulation side. There are different levels of output for different stakeholders: while coastal planners may be most interested in the local sea level change, in particular sea level drop around Greenland having substantial impact on harbor planning, planners of hydropower and protection of settlements would be most interested in frequency of flooding events, extreme melt events. With Greenland's melt approaching a tipping point in which progressive melt triggers accelerated mass loss, this topic expands from Arctic to a global problem.

3.4. Showcases of iCUPE pilot activities towards EVs and SDGs

A general workflow from the iCUPE DSs towards integrated services is illustrated in Fig. 5. The multi-platform data streams covering different thematic domains of the Arctic (cryosphere, atmosphere, terrestrial, and marine) are synthesized into Essential Variables (EVs) This enables development of services that provide insights into accomplishing sustainability in the Arctic in the SDG framework.

We have selected three data pilots (see sections below) that demonstrate the integrated service building capacity utilizing iCUPE data and open data brokerage systems, DIASes and cloud services to realize knowledge provision towards public sector, policy- and decision-making bodies. The general challenge is to identify the links between various types of data, mostly on physical entities like BC, Hg, snow, and ice properties, in the sustainability goals framework. We recognized that the integration of several data sources and targeting EVs is a first step towards a data product that can be further augmented with societal data. In this way, the abstraction level of the data product is growing which makes it more compatible towards the SDG framework's system of goals, targets, and indicators. The Arctic has specific challenges linked for example to opening of shipping routes and increasing access to possible mining sites (e.g., Smith, 2010; Kulmala et al., 2016) because of ice retreat in the changing climate. These targets and indicators are pertinent to SDG 9 (Industry, Innovation and Infrastructures) but at the same

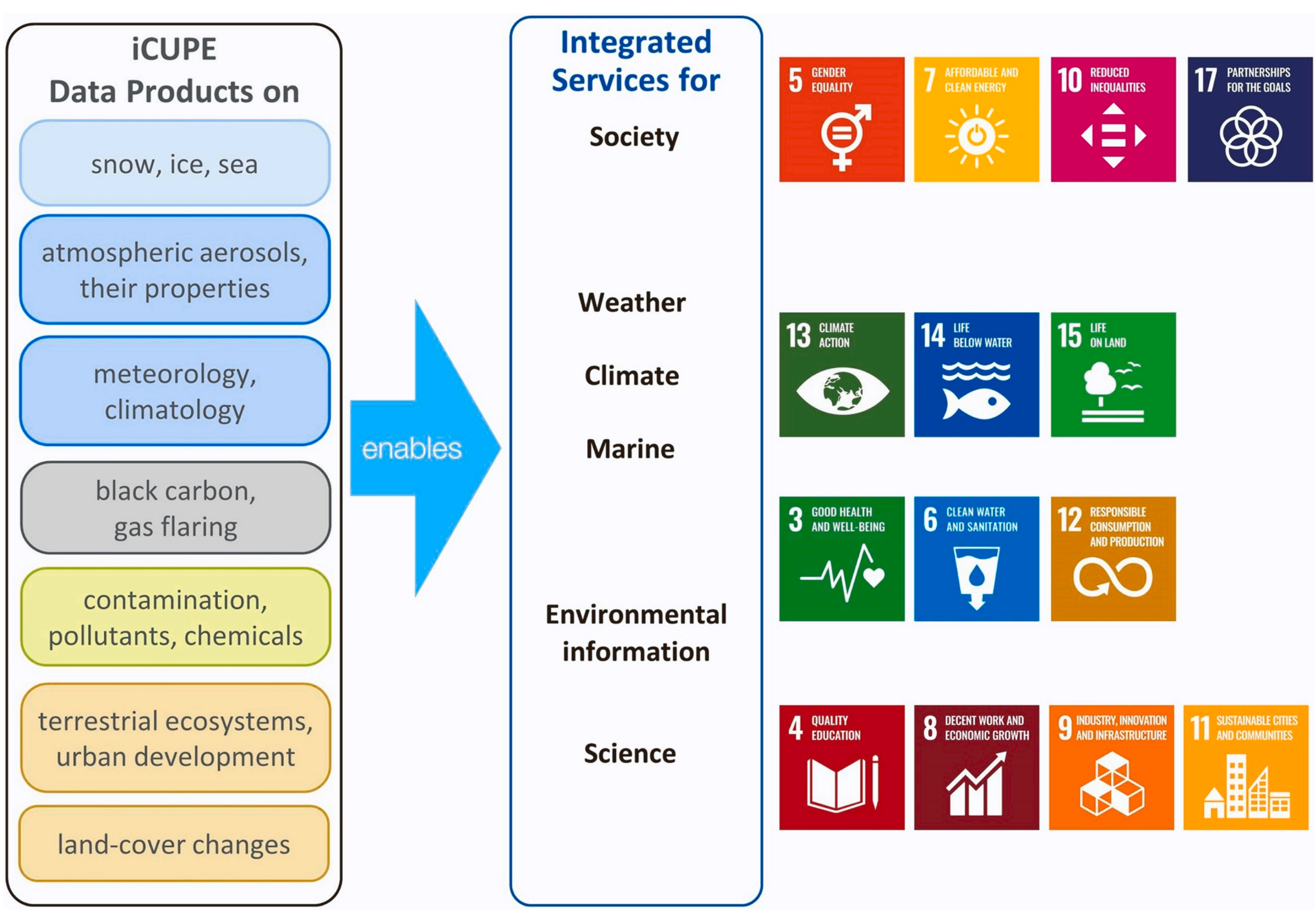

Fig. 5. iCUPE data and potential services with their links to SDGs. The combination of diverse Arctic observations and EVs allows the provision of a multitude of services that feed to the SDGs.

time connected to climate action (SDG 13) for example by degradation of permafrost and receding sea ice.

3.4.1. *VLab application for the snow seasonality in Svalbard islands*

Snow cover is a dynamic interface between the Arctic surface (land, ocean, sea ice) and the atmosphere, and it is an EV of the cryosphere. Data and knowledge about pollution concentrations in the snow are highly relevant for a suite of SDGs (see Section 3.3) and valuable input to implement policies on related emissions.

Here we concentrated on retrieving site-specific relationships between different satellite products aimed at assessing the fractional snow cover (FSC) for selected areas of Ny-Alesund (78.917°N, 11.933°E, Svalbard). This study site was selected considering the contribution of experimental infrastructures supporting the ground-truthing activities: the Zeppelin Observatory, located on a panoramic spot where time-lapse cameras have been in operation since 2000; and the Climate Change Tower with a time-lapse camera deployed in 2018.

We used the VLab platform (Mazzetti et al., 2018; Santoro et al., 2020) to arrange and provide a workflow (Fig. 6a) with data processing and analysis. VLab stands for Virtual Laboratory Platform and facilitates the publication of scientific workflows to support evidence-based decision-making. It was selected since it supports several programming languages and environments, allowing to publish existing models without the need to adapt them to the framework. After the publication on VLab, a model execution can be triggered by users and the framework will handle the ingestion of selected input data, the execution of the model and allows to download outputs. VLab can execute the model on a set of different computing platforms, including cloud platforms such as the European Open Science Cloud, the commercial Amazon Web Services (AWS) cloud and some Copernicus Data and Information Access Services (DIAS) platforms (e.g., CREODIAS, ONDA, Sobloo). This, coupled with a set of interoperability solutions developed in VLab, enables the use of data stored on such platforms, avoiding the need to download the data before starting the execution (move code to data).

The input data sources (Fig. 6a) for the workflow are the Sentinel-2 1 C-level products; the MOD10A1 product provided by the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor; the coastline data service for the Svalbard Archipelago; the parameters useful for the atmospheric correction of the considered product data (the aerosol optical depth, and the columnar water vapor and the columnar ozone content). Considering the occurrence of cloud cover (Salzano et al., 2021) and the limitation due to the revising time of the different platforms, terrestrial photography supports the validation of the estimated relations. In particular, the Zeppelin's camera, operated by the Norwegian Polar Institute, provided a long time-series coupled with a pan-tilt-zoom device (4 different views daily). The Tower's camera provided highly spatio-temporal resolved (hourly) images below a cloud layer. This accounted for a dataset of 930 daily estimations (for 2017–2019) within an area of 10 km^2 with a 20 × 20 m horizontal resolution.

The designed VLab workflow (Fig. 6a) included processing of all input data with a chosen system of coordinates. Images were analyzed in terms of cloud cover and illumination in order to account for darkness which is especially important during the Arctic winter, and foggy or bad weather conditions. The produced snow cover fraction values varied within a range of 0–100.

The iCUPE pilot service provided by this workflow was focused on providing knowledge on snow seasonality occurring in a fragile environment impacted by climate change. Enabling monitoring of FSC as EV and supporting SDGs 14 and 15 are the primary targets of the service mentioned above since the evolution of the snow cover seasonality and its distribution is modifying the exposed ecosystems both in terms of vegetation and biodiversity. Examples of such modifications refer to the wild reindeer species and to the occurrence of periglacial lakes, that represent a relevant ecosystem for the terrestrial food web and by river discharge on coastal communities.

3.4.2. *A concept for a pilot service to reindeer herding community*

For the Arctic, and, for Scandinavia, one of the challenges is that a part of the livelihood and particularly traditions of the local communities and indigenous population rely on the well-being of their reindeers. Hence, services supporting sustainable development of the reindeer herding are valuable and important and linked to the SDGs 2, 8, 12, 13, and 15. Moreover, such a service can promote scientific cryosphere data (from satellites, webcams, models) application to the public and indigenous population which links with SDGs 9 and 10. The pilot is

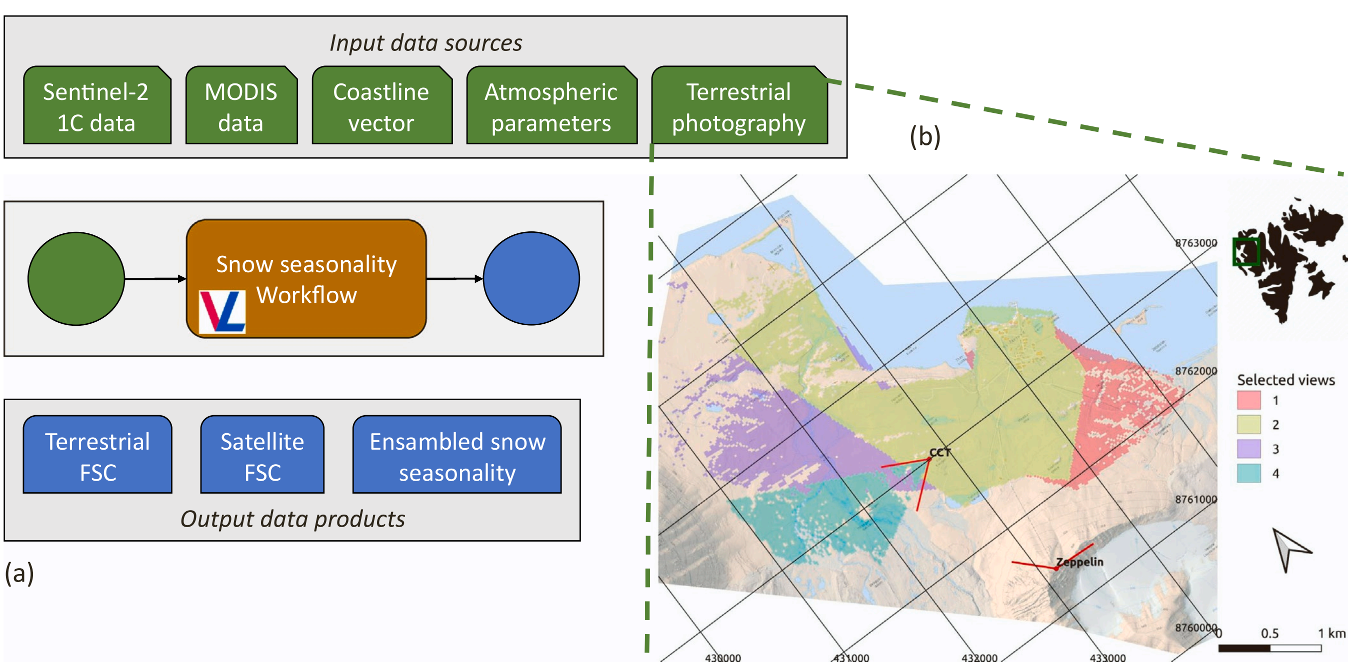

Fig. 6. (a) VLab Workflow to generate a fractional snow cover assessment utilizing local data and linking atmospheric parameters with satellite data products; (b) Location of cameras and panoramic views in the Ny-Ålesund area, Svalbard.

an example of how to augment scientific data of physical objects with societal data and input by implementing a feedback mechanism where user generated content is injected into the process. In that sense, the service also demonstrates a possible way how to include verification and traceability of SDG targets via indicators in a smart way.

Such pilot service, a mobile web-application (web-app), provides easy access to Arctic weather data, Copernicus satellite and webcam-based remote sensed snow and soil products and hydrological forecasts. It can be considered as an information portal for reindeer husbandry communities of Arctic countries contributing to the pilot with their traditional and indigenous knowledge enabling a user driven service.

Data utilized (dataflow is shown in Fig. 7) are Copernicus Sentinels and space missions (e.g., SMOS, SUOMI NPP) for the EO of snow products. The Copernicus Climate Change Service (C3S) forecast and meteorological observations data drives HOPS hydrological deterministic prediction system. Webcams and weather stations provide in-situ data for fractional snow cover processing. Service will make fusion of space-borne EO data, in-situ measurements and modeling data to give hands-on information on snow and frozen soil, short-term and seasonal weather forecasting for reindeer herding community. This will allow planning of supplementary feeding and reindeer corralling for domesticated reindeer and wild deer (for example, Finnish forest reindeer, mountain deer in Svalbard, caribou) conservation activities which are direct links to the SDGs 12, 13, and 15. Feedback from users of the reindeer herder community can ensure tailored visualization and easy access to service products, considering traditional knowledge and experience about Arctic and sub-Arctic nature. In this way, a feedback to inject societal data into the process enables a link towards the SDG targets and indicators.

A successful downstream service needs harmonized data fusion following FAIR data standards. GCOS requirements for EVs will be fulfilled. All helping in improving spatial resolutions, reducing uncertainties, and finally ensuring user friendly access like visualization as WMS and forecasts for selected regions. Handling such big data collections from models and satellites towards web-app requires optimized interfaces like INSPIRE compliant SmartMet server, which will provide the linkage addressing various scientific information simultaneously on the fly and supports access on demand. The frontend of the web-app can be built within a docker environment running on the EU Copernicus DIAS reference system like WEkEO (https://wekeo.eu).

3.4.3. Atmospheric mercury data visualization pilot

A pilot service to access data on atmospheric mercury concentrations was developed using open technologies of Python programming language and Jupyter open-source software notebooks working in a cloud deployable containerized environment. The main purpose was to demonstrate the ability to develop interoperable interfaces to scattered data sources. In expeditions or short-term projects data are often stored in a multitude of possible formats ranging from simple styles such as text or table format files (Excel etc.), compressed data formats or databases with different access protocols and often the need of manual access.

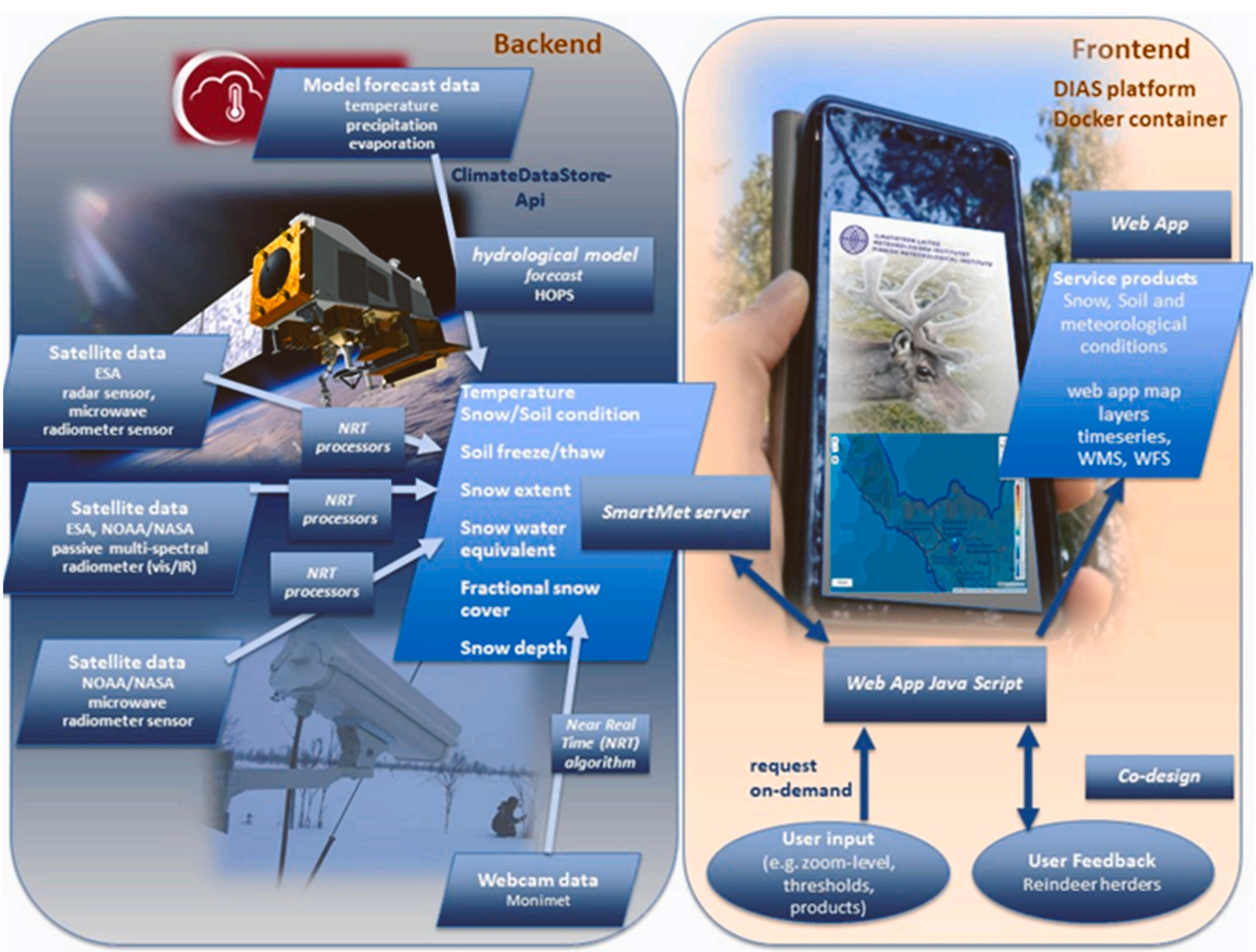

Fig. 7. A schematic chart showing data flow and system implementation plan for a potential pilot service web-application supporting reindeer herding community.

The pilot reads data from the iCUPE data repository, post-process time-series of data and builds a visual representation of the multiyear dataset, augments the already available metadata, like location, with computable metadata like data coverage over the measurement periods. The usage of Jupyter notebook technology for the visualization utilizes the paradigm of computable documents. This gives a flexible handling of different data formats. In this example case, the script decides and commands to add libraries to unpack compressed data only if the injected file format needs this step. In the context of SDGs and integrated services (Fig. 8), the pilot serves environmental information, scientific input data for e.g., modeling, and climate related goals like SDGs 3, 4, 13, 14, and 15 as examples. The pilot also demonstrates the ability to inject highly variable and different kinds of data into larger scale processes like the Reindeer pilot (see Section 3.4.2) and how to enable feedback of societal data depending on policies and regulations to the observational platforms.

4. Conclusions

The Arctic environment is changing rapidly. The driving force originates from anthropogenic activities driven by global megatrends, such as increased use of natural resources, globalization, climate change and population dynamics (e.g., Smith, 2010; Kulmala et al., 2016). The United Nations has defined sustainable development goals (SDGs) which provide a framework to initiate and to support an inclusive decision making towards sustainability. As summarized by Nilsson and Larsen (2020), particularly in the Arctic context, the process of addressing SDGs needs to be inclusive and engage local residents in the development of indicators describing the Arctic environment and societies.

To provide actionable information on the environment relevant to the Arctic related SDGs, comprehensive and harmonized multi-platform observations combining both in-situ observations and satellite remote sensing are crucially needed (Kulmala et al., 2021). Observing the evolution of the Earth's system in the Arctic requires processing of big data, which increases the demand for efficient data streaming, processing, analysis and synergy, so that data streams are transformed into downstream services. For the Arctic, a recent roadmap (Starkweather et al., 2022) underlines, that Arctic observations need to be connected to the social needs of Arctic residents. Indigenous knowledge needs to be incorporated into the observation design framework, so that downstream services ultimately trigger a strong user engagement. This provides equity and inclusivity. Enough resources need to be invested for the development and maintenance. Added value can arise from co-location of observations contributing to different thematic domains in the Arctic (Kulmala, 2018).

The project "Integrative and Comprehensive Understanding on Polar Environments" (iCUPE, Petäjä et al., 2020) developed a suite of comprehensive datasets and workflows that facilitate science-based outcomes contributing towards the Arctic SDGs. Knowledge generation utilizing scientific models to process acquired data is key in a science-informed decision-making process (Nativi et al., 2019). This requires that several challenges related to data and models' interoperability in a multidisciplinary and open environment are addressed (Santoro et al., 2016). Therefore, iCUPE developed a set of pilot workflows and actions including data access that target the definition, support and monitoring capability for EVs and SDGs. In iCUPE we used the Virtual Earth Laboratory (VLab) (Santoro et al., 2020) which is a framework addressing some of these challenges to facilitate the generation of knowledge based on the use of scientific models; it automates the technical tasks required to execute a model on different computing infrastructures, minimizing as much as possible interoperability requirements for both model developers and users. The use of the VLab platform has been tested on integrating multi-source data (remote and terrestrial sensing) into a complex workflow aimed at assessing the snow seasonality reducing the knowledge gap between the skilled developer and the potential end-user. User engagement, especially in the policy context (Fig. 8) and the goal of SDGs, to facilitate change towards sustainable development, needs a process that enables feedback between

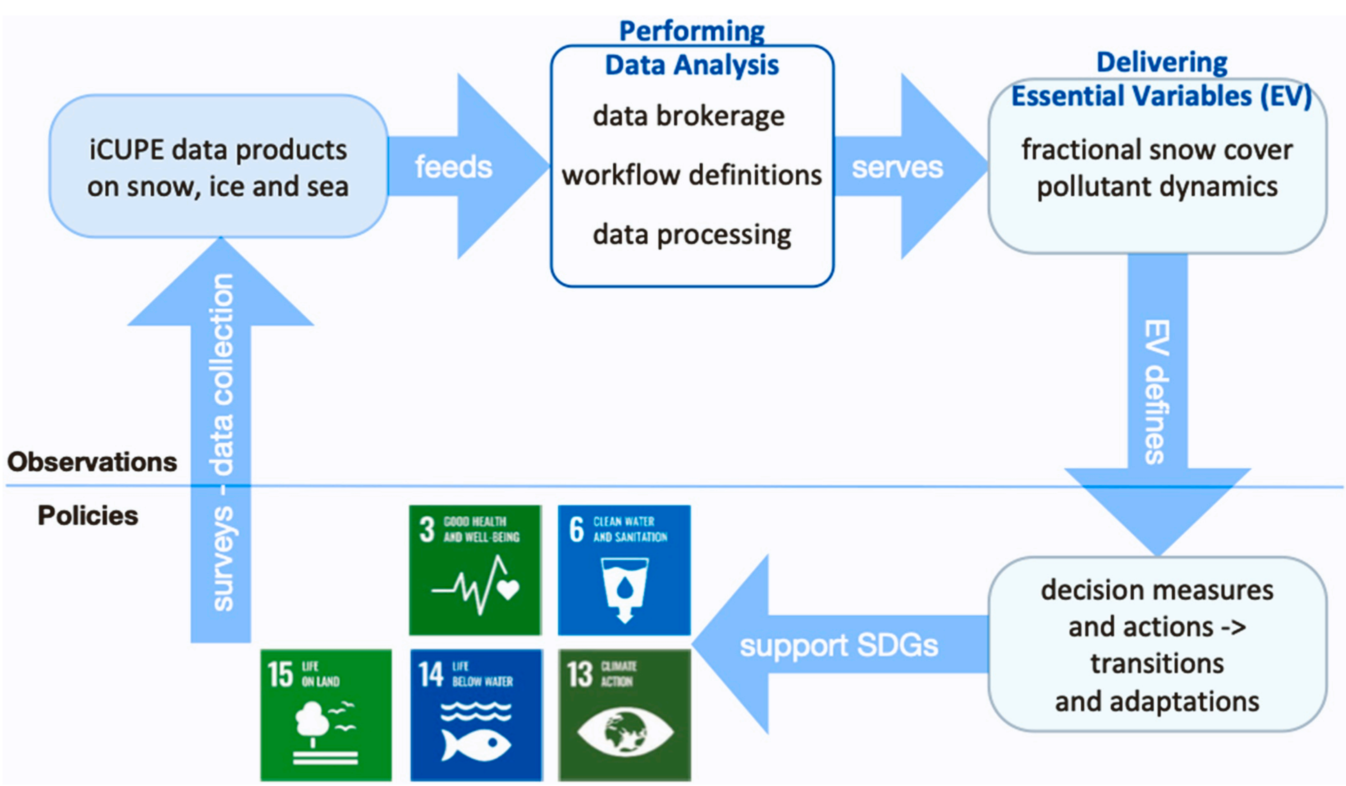

Fig. 8. Generalized example of the iCUPE pilots to enable implementations of actions and transitions to reach SDGs via defining an EV and enabling a continuous surveying structure to track the impact of the sustainable development goals.

the policy domain and the observational domain. In the Arctic context, the SDG framework including its targets and indicators does not always match well to the specific situation of the area. More advanced harmonizing changes or additions to specific targets of Arctic domain could be beneficial.

The iCUPE datasets are connected to several SDGs. In the iCUPE project, the utilization of Arctic datasets to steer the process of reaching sustainable development was tested. The project combined multiscale data to allow informed decisions based on high quality scientific data. Technically, the pilots demonstrate that data and model integration from a wide range of scales can be handled swiftly if applied on modern cloud computing ready solutions. The path to provide knowledge from data by experts (scientists, data providers) to users (local communities, stakeholders, policymakers) has been demonstrated by the iCUPE pilot implementations. A user driven feedback is technically possible when the users can feed in, for example indigenous knowledge, to the data provision process.

Tested scientific knowledge based on pollution data in the Arctic region, therefore, enables us to define and monitor EVs and set up processes to operate via SDGs. The most direct relation of these data is linked with good health and well-being (SDG 3), clean water resources and sanitation (SDGs 6) and life below water (SDG 14), and life on land (SDG 15) because of water and fish are important both local and globally traded food and drinking source; and moreover, developing measures to sustainably ensure the Arctic ecosystems to remain intact. The climate action (SDG 13) plays a prominent role because reducing climate impact, through reductions of CO_2 and short-lived climate forcers (BC, CH_4, O_3) and warming in the Arctic would stabilize the ecosystems with a large impact on the availability of fisheries for nutritional, economical but also cultural needs of the local, especially indigenous, and global societies which invoke the SDGs 5 (Gender equality), 9 (Industry, innovation and infrastructure), 10 (Reduced inequalities) and 12 (Response consumption and production). Pollution emission mitigation measures also involve promotion of affordable and clean energy (for SDG 7), clean air and healthy living conditions (for SDG 3) and climate adaptation benefits (for SDG 13). In this respect iCUPE contributed to the work of the Arctic Council Arctic Monitoring and Assessment Programme on Short-Lived Climate Forcers including the use of observations for evaluation of models run with state-of-the-art emission inventories and to the related EU Action on Black Carbon in the Arctic (EUA-BCA) which reviews and proposes black carbon emission reduction measures for particular sectors that affect the Arctic such as gas flaring.

The iCUPE datasets can also be considered as quality-controlled data collection of the current Arctic conditions. These can be later contrasted against new observations but also benchmarking datasets for future projections. For example, it is critical to evaluate the potential risks associated with mercury dispersed via the meltwater into the Arctic Ocean from Greenland ice sheets. In a similar manner, transport of atmospheric pollutants to the Arctic as well as mercury, Persistent Organic Pollutants and other pollutants released from thawing permafrost and snow need to be monitored also in the future.

CRediT authorship contribution statement

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Synopsis

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