POLARIN

POLAR RESEARCH INFRASTRUCTURE NETWORK

Deliverable 1.5. Polar knowledge gaps and the potential of POLARIN infrastructure in addressing these

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SUMMARY

Our ability to observe, understand, and predict polar change relies on our combined observational capacity, including remote sensing, modelling, and in-situ observations. In-situ observations are crucial but often scarce in polar regions due to logistical challenges and harsh environments. This deliverable builds on a framework for graphical products related to the six natural science related POLARIN themes (WP4), providing insights into current state of knowledge for selected key prioritised variables that here is used to identify potential knowledge gaps and the potential for POLARIN infrastructures to cover these. The knowledge gap analysis compares remote sensing and data upscaled products (pan-Arctic coverage modelled from in-situ observations), CMIP6 Earth System Models, and in-situ data for the themes 'Terrestrial Carbon Cycle and Permafrost, and 'Polar Ecosystems and Biodiversity' – more specifically Soil Organic Carbon and Above Ground Biomass, respectively. The deliverable thus identifies geographical gaps that POLARIN infrastructures can address.

1. Introduction

Our ability to observe, understand and predict polar changes depends on our combined observational capacity. Remote sensing, modelling and in-situ observations add to our knowledge of current state and dynamics. In-situ observations are often scarce in polar areas challenged by logistics, costs of operations, and a remote and harsh environment, yet these are important for verifying remote sensing observations and feeding into modelling efforts. The geographical distribution of in-situ observations, level of standardisation (applied methodology, units, etc.) and level data sharing have implication for the representativity of our observations.

This deliverable is building on a framework for graphical products developed in WP4 Data Services and Customised Products, providing information about our current knowledge of selected variables related to six of the POLARIN themes. The graphical products will here be used to identify potential observational gaps in the in-situ observations that can be filled by POLARIN infrastructures (e.g. through the POLARIN Transnational Access programme).

This deliverable will include variables related to the themes 'Terrestrial Carbon Cycle and Permafrost' (Soil Organic Carbon) and 'Polar Ecosystems and Biodiversity' (Above Ground Biomass. It will be followed by additional deliverables adding variables related to other POLARIN themes.

The deliverable has been developed for the terrestrial Arctic domain but will be refined based on feedback and applied also in marine, atmospheric and Antarctic domains in the future.

2. Main Objectives

The purpose of the gap analysis is to compare values of in-situ observation sites with values generated by available remote observations, data upscaled products and CMIP6 Earth System Models (ESM) for selected variables in polar regions. This can be used to evaluate the representativeness of existing in-situ observations and the potential for POLARIN infrastructures to fill potential observational gaps.

Deliverables under this task will provide gap analysis related to key variables within the POLARIN themes:

1. Sea-Ice and Polar Oceans in the climate system
2. Polar ice sheets, glaciers and sea level
3. Terrestrial carbon cycle and permafrost (delivered here)
4. Polar Ecosystems and biodiversity (delivered here)
5. Atmosphere dynamics and chemistry
6. Paleoclimate processes and variability

Selection of key variables is inspired by *Deliverable 1.4 - Overview report of existing science priorities by major Arctic and Antarctic organisations and validation/calibration needs by in-situ observation, remote sensing, and modelling communities*. Variables are also selected based on the available data from remote sensing, data upscaled products (pan-Arctic coverage modelled from in-situ data sets) and in-situ observations.

Data sources: Remote sensing data are obtained from the ESA Climate Change Initiative https://climate.esa.int/en/data/#/dashboard. Outputs of CMIP6 Earth System Models (ESM) are applied using the same unit and geographical coverage. In-situ data are gathered from existing open access thematic repositories.

2.1. General description of gap analysis

The current analysis focuses on the terrestrial Arctic domain but will be expanded to other domains. The analysis divides the Arctic into grid cells. Remote sensing, data upscaling products and CMIP6 ESM data are used to assess the given variable on the pan-Arctic scale. The pan-Arctic gridded observations are then compared to the in-situ observation values from relevant open access repositories including the selected variable.

To provide a comparative analysis of variability across observation and modelled data across the Arctic, the analysis contains 1) remote sensing, data upscaling products and CMIP6 ESM maps using the same units and similar geographical coverage with overlay of in-situ observation sites and POLARIN infrastructures, and 2) box plots comparing the variability between maps, in-situ observations (existing thematic repositories) and terrestrial POLARIN infrastructure locations.

Probabilistic distributions functions for remote sensing, data upscaling product and CMIP6 ESMs are then compared to probabilistic distribution functions for in-situ observations to identify variable values where in-situ observations are underrepresented compared to grid cells covering the entire Arctic domain. By subtracting the in-situ function from the remote sensing/data upscaling product/CMIP6 ESM functions we identify differences in distribution functions - higher positive values indicate a gap and the need for more in-situ observations in locations with this particular variable value.

We then look at the remote sensing/ data upscaling product/CMIP6 ESM values in the grid cells where POLARIN stations are located and if these values fall within an identified gap, the infrastructure has the potential to fill an observational gap through targeted Transnational Access. It is worth noting that local variability may affect the suitability of a POLARIN station to fill a gap. Hence local analysis is needed to identify the most suitable location for the new observing site.

2.2. Gap analysis 2025

POLARIN themes and selected variables

Theme 3: Carbon Balance and Permafrost:

a. Variable: Soil Organic Carbon

Theme 4: Polar Ecosystems and Biodiversity:

b. Variable: Above Ground Biomass

2.2.1 Above Ground Biomass

Vegetation biomass changes can indicate shifts in climate patterns. For example, increased biomass can be triggered by warmer temperatures, which can lead to greening that impacts habitat suitability for various species. Vegetation also plays a crucial role in the carbon cycle by absorbing carbon dioxide during photosynthesis. Monitoring biomass helps scientists understand how much carbon is being sequestered in polar regions and how changes in vegetation affect global carbon dynamics.

Variable: Above Ground Biomass - $kgCm^{-2}$

Results:

Figure 1 and 2 show similar medians for remote sensing and CMIP6 model output, but higher variability for the modelled output. Variable values for grid cells with POLARIN stations reveal a slightly lower median and significant smaller variability for remote sensed data, while model data show similar median, similar 50% variability, but smaller total variability indicating that POLARIN stations are not representative of the entire Arctic domain. In-situ data show lower median and variability compared to both remote sensing and model output, indicating underrepresentation in some variable value ranges across the Arctic.

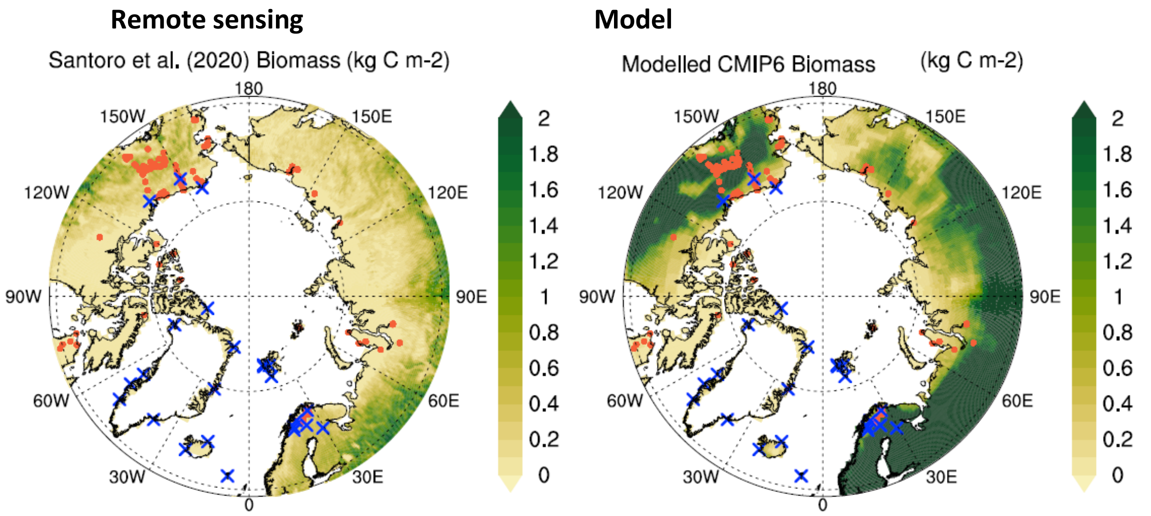

Figure 1. Map depicting remote sensing (Santoro *et al*., 2020) and CMIP6 ESM (CMIP6 Biomass, retrieved from López-Blanco *et al.,* 2024) values for Above Ground Biomass overlaid by in-situ observation sites (Berner *et al*., 2014) (orange dots) and POLARIN research stations (blue x).

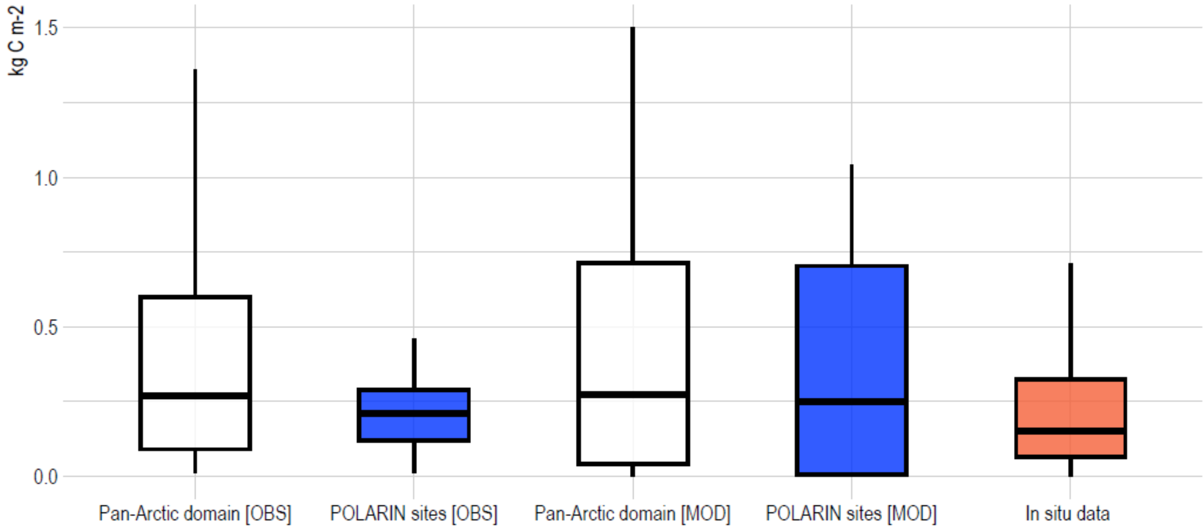

Figure 2. Box plots depicting median (thick horizontal line), 50% /box) and total (vertical line) variability of grid cells for a) the pan-Arctic domain (remote sensing (OBS) and CMIP 6 models (MOD) (white boxes), b) grid cells containing POLARIN research stations (blue boxes), and c) in-situ observations, for Above Ground Biomass.

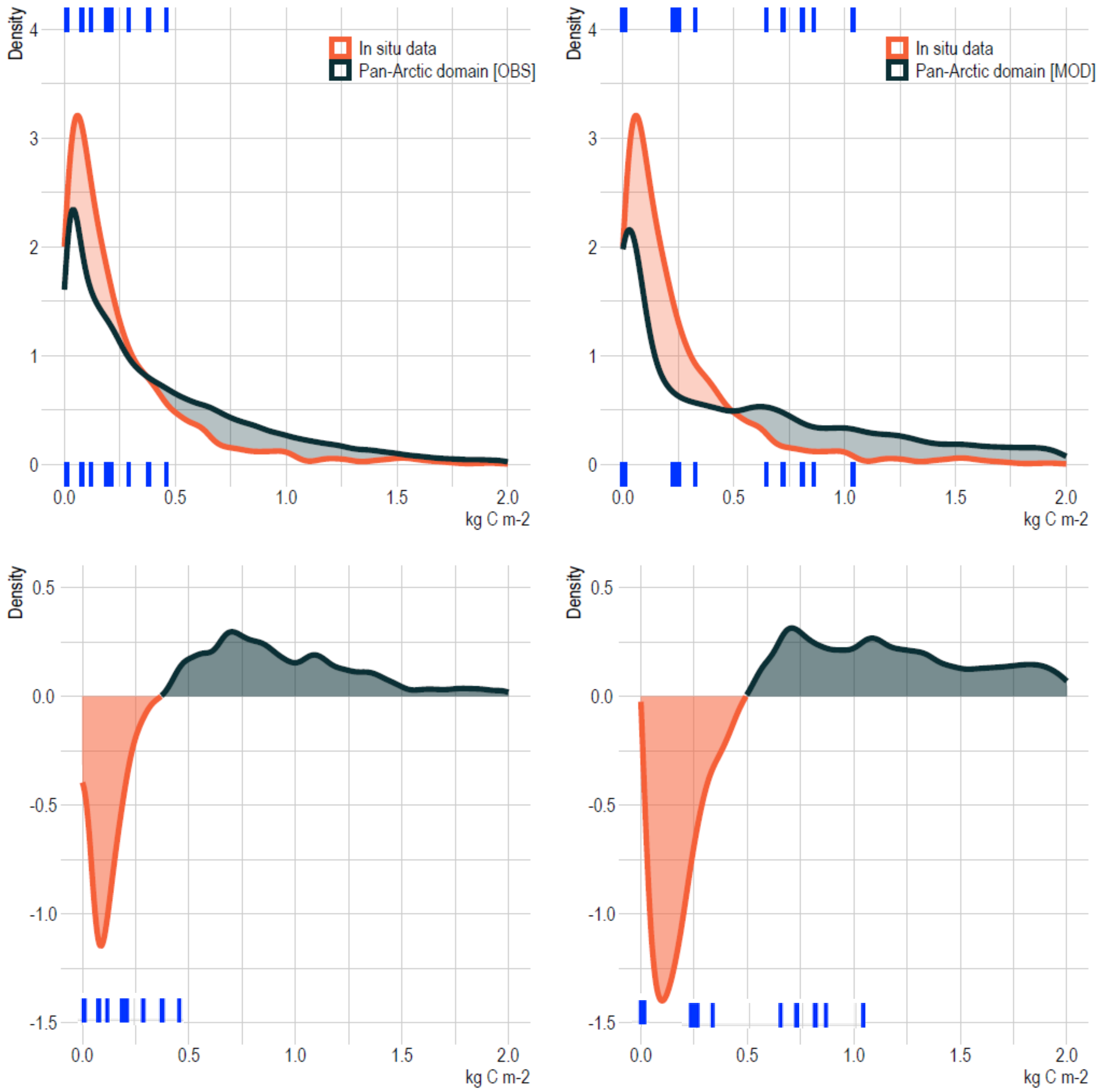

Figure 3. Above: Probabilistic distribution functions for the pan-Arctic domain (black) and for in-situ observations (orange) – left: remote sensing, right: CMIP6 ESM. Below: Cumulative distribution function for in-situ subtracted from the pan-Arctic domain – left: remote sensing, right: CMIP6 ESM. Blue lines indicate variable values for POLARIN research stations where there is pixel information. Positive values mean overestimation of the pan-Arctic region compared to the in-situ data, and negative values, the other way around.

Key insights

The probabilistic distribution functions show that the number of in-situ sites exceeds the number of grid cells for the lower ranges of Above Ground Biomass, while the number of grid cells exceeds the number of in-situ observations for higher values (with the shift occurring at c. 0.325 and c. 0.5 kgCm^{-2} for remote sensing and CMIP models respectively). This indicates that areas with values above these figures are potentially underrepresented in the in-situ data set.

Stations that could fill a knowledge gap for Above Ground Biomass:

The location of blue lines shows remote sensed and modelled values for grid cells with POLARIN stations and thus stations located in the positive range of below graphs in Figure 3 have the potential to fill a gap.

Gap in variable- Above Ground Biomass:

- Remote sensing value > c. 0.325 $kgCm^{-2}$
- CMIP6 ESM values> c. 0.5 $kgCm^{-2}$

Stations that can fill a gap identified by:

Remote sensing:

- Oulanka Research Station, Pallas-Sodankylä Research Stations

CMIP6 ESMs:

- Western Arctic Research Center, Tarfala Research Station, Abisko Scientific Research Station, Oulanka Research Station, Kilpisjärvi Biological Stations, KEVO Research Station, Pallas-Sodankylä Research Stations, Toolik Field Station

Data sources:

- ❖ Remote sensing data (left map (OBS)): Santoro *et al*. (2020) https://dx.doi.org/10.5285/af60720c1e404a9e9d2c145d2b2ead4e
- ❖ Modeled data (right map (MOD)): All CMIP6 modelling datasets used in this study can be accessed and downloaded freely from ESGF repositories (for example, https://esgf-node.llnl.gov/projects/cmip6/ and https://esgf-data.dkrz.de/search/cmip6-dkrz/).
- ❖ In-situ data: Berner *et al.* (2014) https://doi.org/10.1038/s41597-024-03139-w

Terrestrial infrastructure locations: Maps include markers for POLARIN sites (crosses), indicating opportunities for data collection points.

References:

Berner, L.T., *et al.* (2014). The Arctic Plant Aboveground Biomass Synthesis Dataset. *Sci Data* 11, 305 (2024).
Santoro, M., *et al*. (2020). The global forest above-ground biomass pool for 2010 estimated from high-resolution satellite observations. Earth System Science Data, 13, 3927-3950.

2.2.2 Soil Organic Carbon

Polar regions (especially the Arctic) store vast amounts of carbon in their soils. As the climate warms, permafrost thaws, releasing stored carbon into the atmosphere as carbon dioxide and methane, potent greenhouse gases. Monitoring Soil Organic Carbon helps track these emissions and understand their impact on global climate change. Soil Organic Carbon is also a key indicator of soil health, influencing soil structure, fertility, and biodiversity that are shaping polar ecosystems.

Variable: Soil Organic Carbon - kgCm^{-2}

Results:

Soil Organic Carbon cannot be measured by remote sensing. Instead, data upscaled products derived of in-situ data (Hugelius *et al*., 2014) and CMIP6 ESMs are used to assess gaps in in-situ observations. Upscaled Soil Organic Carbon product shows higher median and higher variability than CMIP6 ESM data. In-situ observations and POLARIN station grid cells have considerably lower median and variability for both upscaled and CMIP6 ESM data indicating that they are underrepresented (Figure 5 and 6) in areas with high Soil Organic Carbon values.

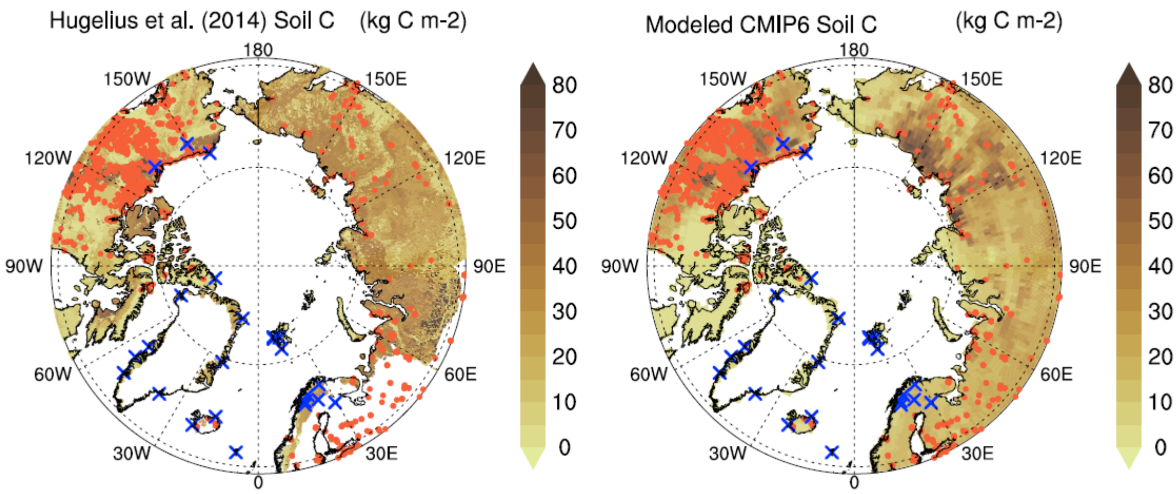

Figure 4. Map depicting upscaled modelled data (Hugelius *et al.*, 2014) and CMIP6 ESM (CMIP6 Soil C, retrieved from López-Blanco *et al.,* 2024) values for Soil Organic Carbon overlaid by in-situ observation sites from the World Soil Information Service (WoSIS - https://www.isric.org/explore/wosis)(orange dots) and POLARIN research stations (blue x).

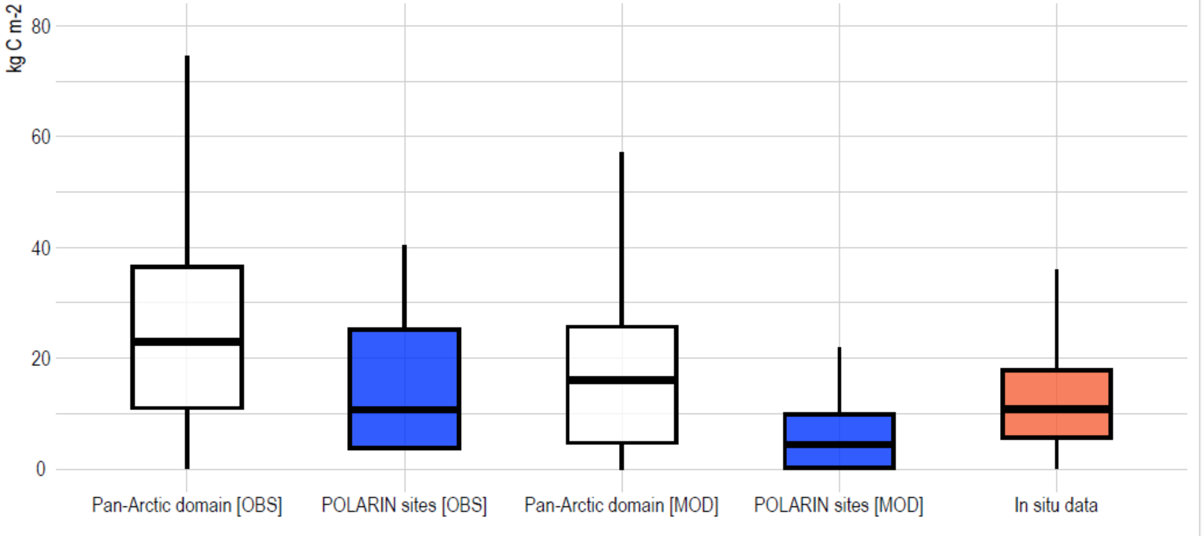

Figure 5. Box plots depicting median (thick horizontal line), 50% /box) and total (vertical line) variability of grid cells for a) the pan-Arctic domain data upscaled product (OBS) and CMIP 6 models (MOD) (white boxes), b) grid cells containing POLARIN research stations (blue boxes), and c) in-situ observations, for Soil Organic Carbon.

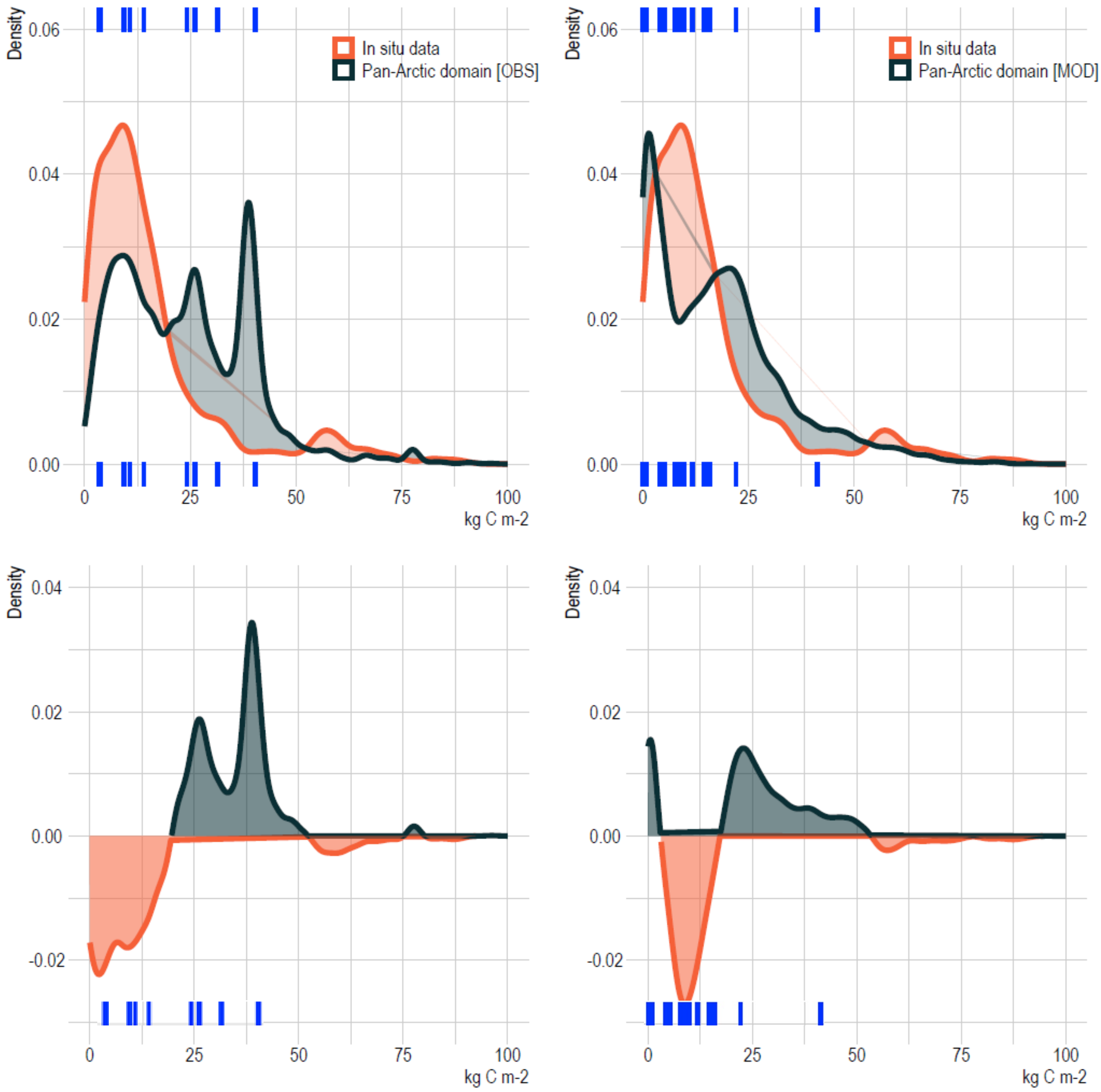

Figure 6. Above: Probabilistic distribution functions for the pan-Arctic domain (black) and for in-situ observations (orange) – left upscaled from Hugelius *et al.*, 2014, right CMIP6 ESM derived from López-Blanco *et al*., 2024. Below: Probabilistic distribution function for in-situ subtracted from pan-arctic domain – left upscaled from Hugelius *et al.*, 2014, right CMIP6 ESM. Blue lines indicate variable values for POLARIN research stations where there is pixel information. Positive values mean overestimation of the pan-Arctic region compared to the in-situ data, and negative values, the other way around.

Key insights:
The cumulative distribution functions for the data upscaling products and CMIP6 ESM data (Figure 6) show that the number of in-situ sites is lower than the number of panarctic grid cells for the Soil Organic Carbon ranges of c. 20 – 52,5 kg C m-2. This indicate that areas with values in this range are potentially underrepresented. The CMIP6 ESM furthermore identifies the extreme low Soil Organic Carbon values (c. < 5 kg C m-2) as underrepresented in the in-situ data set, indicating an observational gap.

Stations that could fill a knowledge gap for Above Ground Biomass:
The location of blue lines shows data upscaling model and CMIP6 ESM values for grid cells with POLARIN stations and thus stations located in the positive range of below graphs in Figure 6 has the potential to fill a gap.

Variable gap - Soil Organic Carbon:

- Data Upscaling Product: c. 20 – 52,5 kg C m-2.
- CMIP6 ESM: < 5 kg C m-2 and c. 20 – 52,5 kg C m-2.

Stations that can fill a gap identified by:

Data upscaling Products:

- Western Arctic Research Center, Tarfala Research Station, Abisko Scientific Research Station, Kevo Research Station, Arctic Station, Zackenberg Research Station

CMIP6 ESMs:

- Western Arctic Research Center, Toolik Field Station

Data sources:

- ❖ Upscaled modelled data (left map (OBS)): Hugelius *et al*. (2014) https://doi.org/10.5194/bg-11-6573-2014
- ❖ Modelled data (right map (MOD)): All CMIP6 modelling datasets used in this study can be accessed and downloaded freely from ESGF repositories (for example, https://esgf-node.llnl.gov/projects/cmip6/ and https://esgf-data.dkrz.de/search/cmip6-dkrz/).
- ❖ In-Situ data: The World Soil Information Service (WoSIS - https://www.isric.org/explore/wosis

Terrestrial infrastructure locations: Maps include markers for POLARIN sites (crosses), indicating opportunities for data collection points.

References:

Hugelius, G., Strauss, J., Zubrzycki, S., Harden, J. W., Schuur, E. A. G., Ping, C.-L., Schirrmeister, L., Grosse, G., Michaelson, G. J., Koven, C. D., O'Donnell, J. A., Elberling, B., Mishra, U., Camill, P., Yu, Z., Palmtag, J., and Kuhry, P.: Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps, Biogeosciences, 11, 6573–6593, https://doi.org/10.5194/bg-11-6573-2014, 2014.
World Soil Information Service (WoSIS - https://www.isric.org/explore/wosis)

3. Conclusions

The two assessed variables show indications of being underrepresented in some ranges of values when compared to the pan-Arctic scale represented by remote sensing, data upscaling products and CMIP6 ESMs. POLARIN stations located in the underrepresented value ranges thus have potential to fill af knowledge gap for the variables.

<u>Variable gap and POLARIN stations - Above Ground Biomass:</u>
Remote sensing > c. 0.325 $kgCm^{-2}$:
- Oulanka Research Station, Pallas-Sodankylä Research Stations

CMIP6 ESM: > c. 0.5 $kgCm^{-2}$:
- Western Arctic Research Center, Tarfala Research Station, Abisko Scientific Research Station, Oulanka Research Station, Kilpisjärvi Biological Stations, KEVO Research Station, Pallas-Sodankylä Research Stations, Toolik Field Station

<u>Variable gap and POLARIN stations - Soil Organic Carbon:</u>
Data Upscaling Product: c. 20 – 52,5 kg C m^{-2}:
- Western Arctic Research Center, Tarfala Research Station, Abisko Scientific Research Station, Kevo Research Station, Arctic Station, Zackenberg Research Station

CMIP6 ESM: < 5 kg C m-2 and c. 20 – 52,5 kg C m^{-2}:
- Western Arctic Research Center, Toolik Field Station

It is important to note that local variability may affect the suitability of a POLARIN station to fill a gap. Hence local analysis is needed to identify the most suitable location for the new observing site.

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