

# Response to Community Comments

## Manuscript ESSD-2026-299

*"An Ensemble Dataset of Permafrost Thaw Conditions for Northern High Latitudes Using Open Satellite Data"*

Dear Dr. Way,

Thank you for your constructive comments, the relevant literature you suggested, and references to the Nordicana D Network, which provides additional borehole sites to enrich our product evaluation. Your extensive experience in cryosphere and northern environment research is highly valued and greatly appreciated. Please find below our point-by-point responses to your comments. We will also revise the manuscript accordingly after the review window is closed.

### **1. Spatial uncertainties associated with averaging multiple global datasets to generate an ensemble product, referencing to relevant studies of the coastal permafrost in northern Canada**

This comment is related to our process of two ensemble products: Permafrost Percent (PP) and MAGT from three publicly available maps: the Obu map, the NIEER map, and the ESA Permafrost\_CCI map (represented by the 1997-2021 average). All three datasets are available at approximately 1 km grid size. Because only these three maps are publicly available globally, we adopted a median-based ensemble approach to achieve a more robust estimate than a mean (average) approach.

We highly value your comments regarding spatial uncertainties in areas where the three maps differ substantially from one another. We agree that a simple median-based ensemble may propagate these uncertainties and potentially lead to erroneous indications in these areas, thereby limiting its applicability in other studies. To further evaluate this issue, we compared the spatial distributions of the three source maps (Obu, NIEER, ESACCI) with the median ensemble product we adopted for both PP and MAGT (Fig.1).

For PP, all three source maps (Fig.1a-1c) show strong agreement in the interior of the study region corresponding to the continuous permafrost zone (PP=100%). Greater discrepancies occur farther south characterized by discontinuous, sporadic and isolated permafrost. Overall, the hot and cold spots of the PP difference are localized, occurring as smaller patches in local areas. One notable example is the ESACCI PP map, which exhibits strong overestimation along the south margin of Siberia in northern Asia (the red patches in Fig.1c). Moreover, all three source maps indicate a more northerly limit of permafrost than that shown by the IPA map as the background layer. This is consistent with findings from past studies in literature, attributing to 1) satellite-based products capturing finer spatial details than the IPA map that was developed from expert knowledge, and 2) permafrost retreat since the publication of the IPA map, which may date back to the 1950s in some regions. Our ensemble PP product provides an updated baseline representation of permafrost distribution while reducing the influence of uncertainties from individual PP maps.

For MAGT, the three source maps also exhibit notable regional differences in their spatial patterns. For example, in central Siberia, the Obu map (Fig.1d) shows substantial underestimation, whereas the NIEER map (Fig.1e) contains a concentrated cluster of strong overestimations. The ESACCI map (Fig.1f) displays several localized hot spots in northern Asia and cold spots in the High Arctic of northern Canada. By selecting the median value from the three maps, we expect our ensemble MAGT product to reduce these region-specific uncertainties and biases associated

with individual MAGT maps, thereby providing a more robust representation of global permafrost thermal conditions.

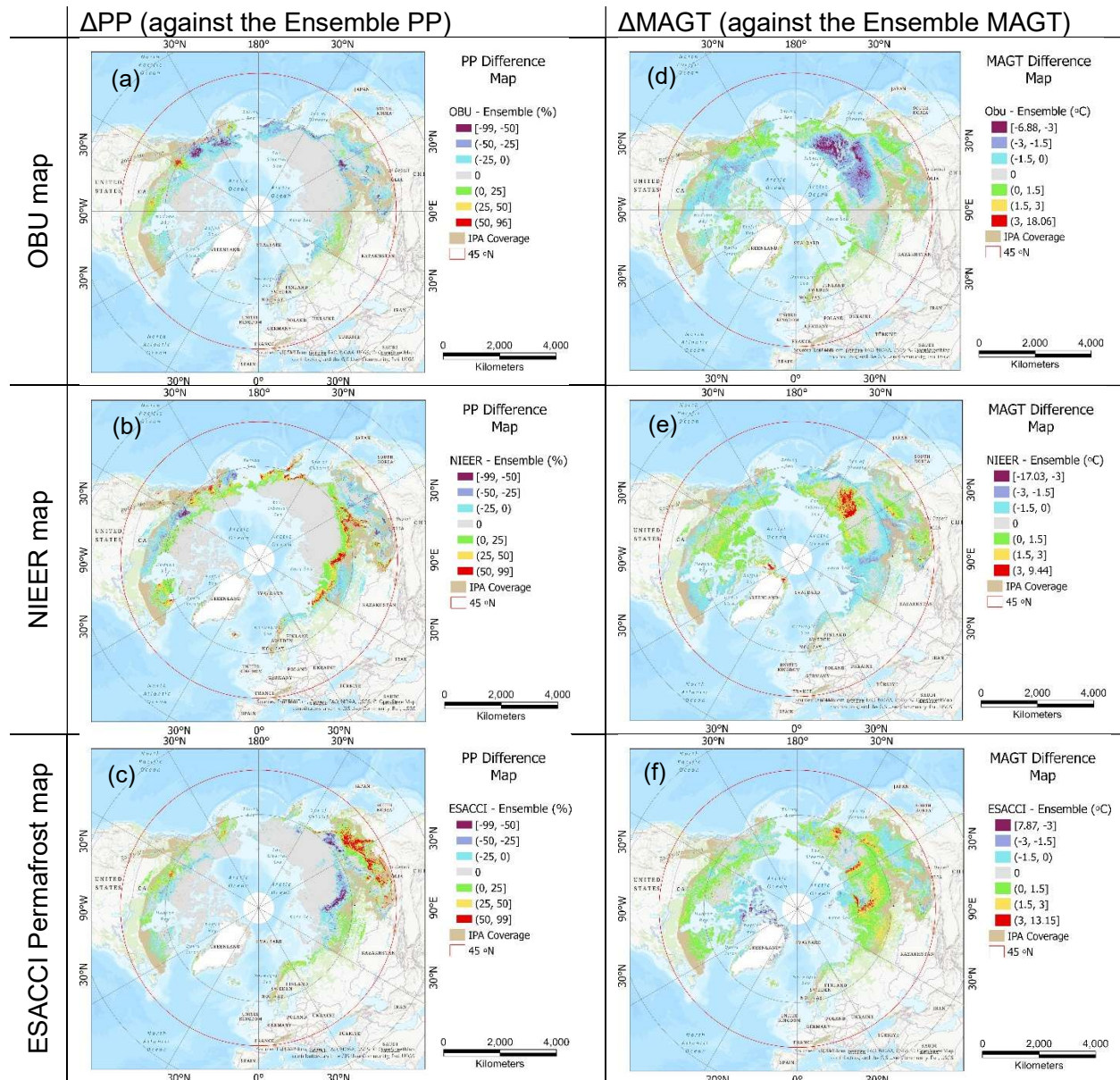
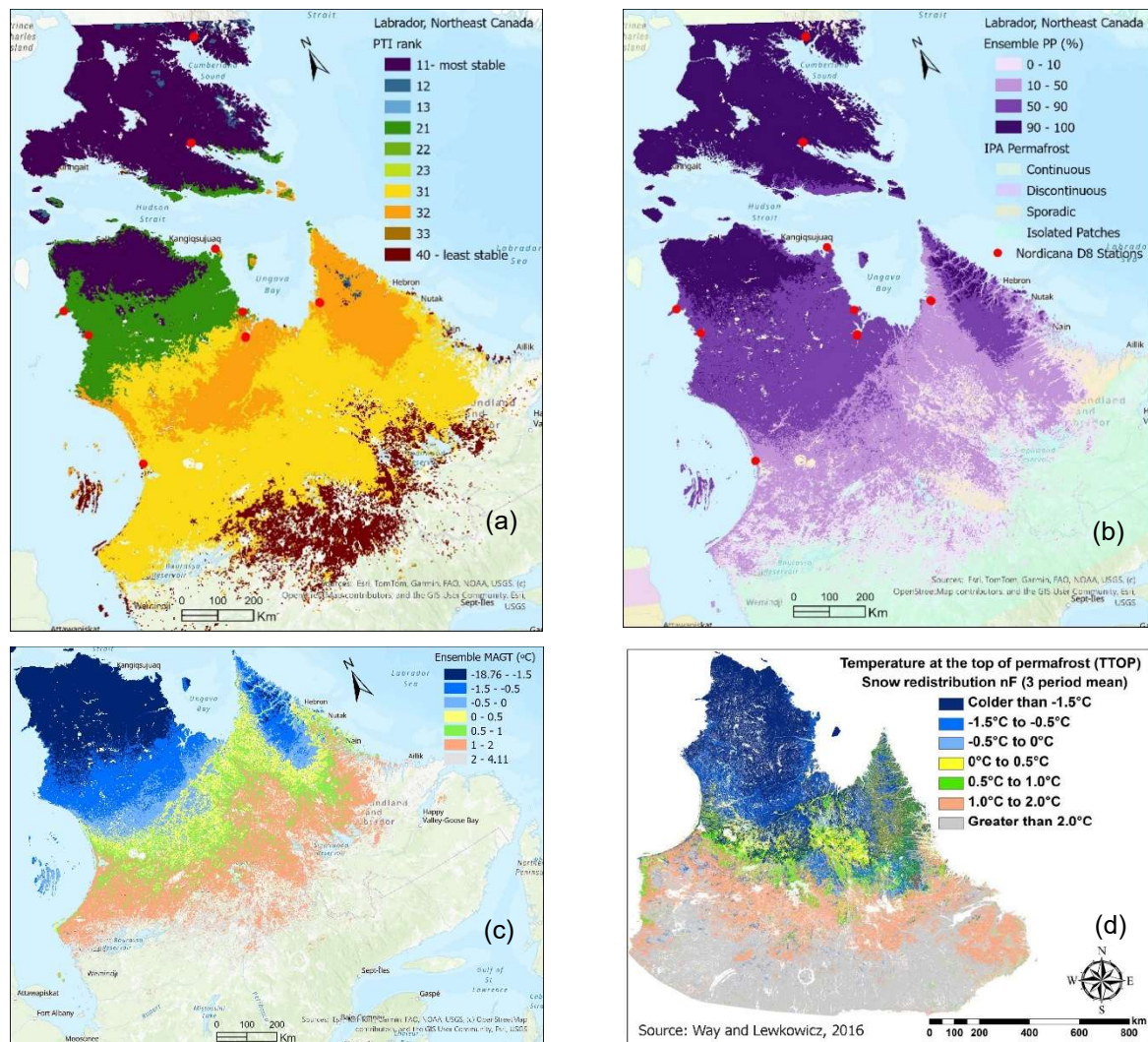


Figure 1 Differences of the three source maps (Obu, NIEER, ESACCI) against the ensemble product of our study. The left column (a–c) shows the PP differences, and the right column (d–f) shows the MAGT differences. Areas in light gray (zero difference) represent locations where the ensemble value was selected. The light brown background outlines the IPA permafrost coverage.

Particularly on the Quebec-Labrador Peninsula (hereafter referred to as Labrador Peninsula), all three source maps in Fig.1 provide reasonably consistent estimates of PP and MAGT, with  $\Delta PP$  ranging from -25% to 25% and  $\Delta MAGT$  from -1.5°C, 1.5°C relative to the ensemble product. Noticeably, the NIEER PP in Fig.1b has a few small clusters of PP overestimation as shown in red and yellow tones.

To facilitate a more detailed visual comparison, we exported regional maps using the Canada Lambert Conformal Conic projection and coordinate system (Fig.2). Our PTI map (Fig.2a) indicates a clear geographic gradient in thawing potential, transitioning from the most stable conditions (PTI = 11) in the north to the least stable (PTI = 40) in the south. The northern portion of the peninsula is dominated by PTI ranks 11 and 21. The absence of Tier-2 levels (i.e., 12, 13, 22, 23) suggests that both MAGT and ALT remain stable (no trend), reflecting the high stability of cold and cool permafrost in this region. The southern portion of the peninsula is primarily characterized by PTI rank 31. Areas with PTI of 40 in the south end are mostly isolated patches with MAGT exceeds 3°C, which agrees with the expected behavior of warm and highly vulnerable permafrost. However, the occurrence of PTI rank 32 in the central plains (elevation < 500 m) and in coastal mountains along the Labrador Sea may deserve further investigation.



**Figure 2 Visual comparison of permafrost conditions across the Labrador Peninsula: PVI (a), Ensemble PP (b) and Ensemble MAGT (c), together with a modeled MAGT map (d) of Way and Lewkowicz (2016), which was derived using the snow-redistribution freezing n-factor parameterization. The red dots in (a) and (b) mark the borehole sites from the Nordicana D8 Network, including several sites in Baffin Island in the north. Note: This figure is provided solely for our response purpose and will not be included in the manuscript.**

In the ensemble PP map (Fig.2b), permafrost distributions of the region follow a latitudinal pattern similar to that reported by Way and Lewkowicz (2016) and several other regional maps, including

the National Atlas of Canada (Heginbottom et al., 1995) and those of Payette (2001) and Gruber (2012), all compared in Way and Lewkowicz (2016). The delineation of permafrost zones in these maps varies across the peninsula, attributing to differences in methodologies, environmental characterization, and the spatial and temporal scales considered, as described in Way et al. (2018).

In this response, we further compared our ensemble MAGT (Fig.2c) with a snapshot of your snow-modified TTOP map (Fig.2d) by Way and Lewkowicz (2016). Although the two maps exhibit similar latitudinal patterns, notable differences are observed in the central portion of the peninsula, our ensemble MAGT shows extensive areas with MAGT in the ranges of 0–0.5°C and 0.5–1°C, whereas the snow-modified TTOP map displays a more heterogeneous spatial pattern adjusted by environmental conditions such as localized snow cover variability. Overall, our ensemble MAGT presents generally warmer ground temperatures than your snow-modified TTOP map.

We especially thank you for drawing our attention to your findings regarding the significant underestimation of permafrost along the Labrador Coastline (Wang et al. 2023). In the north of Happy Valley-Goose Bay and south of 55°N, our ensemble PP map (Fig.2b) depicts sparse fragments within a mixed zone of sporadic permafrost and isolated patches. Yet the peatland permafrost inventory presented by Wang et al. (2023) evidences the presence of permafrost complexes associated with palsa bogs and peat plateaus along the coastline, which seems to be underestimated in our ensemble map.

The Nordicana D borehole sites marked in Fig.2a-2b are discussed in the following response.

#### **Proposed revision in manuscript:**

We will add a new subsection to “3.3.3 *PTI map accuracy and uncertainty assessment*” in the revised manuscript. The analyses and discussions presented in our responses above, including Fig.1, will be incorporated into this subsection. The newly suggested references will be properly cited. In particular, we will elaborate on spatial uncertainties among different satellite data products, and emphasize the importance of careful environmental characterization to better interpret and mitigate these uncertainties for future applications.

In addition, our discussion about the Labrador Peninsula, including the findings summarized in Fig.2, will be incorporated into the Discussion section. Given its regional focus and the space limitations of the manuscript, Fig.2 will not be included in the revised manuscript.

## **2. Under-representation of ground borehole data, referencing to the Nordicana D network in northeastern Canada**

We appreciate your reference to the Nordicana D Network, which substantially enriches our collection of in-situ ground observation dataset for evaluating our PTI prediction. Among its datasets, the D8 (SILA Borehole and Near-Surface Ground Temperature) provides borehole records of daily temperature measured at different depths, enabling our assessment of MAGT and ALT trends.

The D8 Network comprises 46 borehole and HOBO monitoring sites across the Nunavik–Nunavut region (Allard et al., 2024). The HOBO sites measure only near-surface temperature and were excluded from our analysis. Each borehole site is equipped with thermistor cables that record ground temperature at multiple depths ranging from approximately 3 to 20 m, with data available at four temporal resolutions (hourly, daily, monthly, yearly). Only 18 borehole sites contain time

series of temperature since 2000 that satisfy our data requirements. Some sites were excluded because of insufficient borehole depth (e.g., 3 m), significant data loss, or anomalous records in daily temperature profiles. Ultimately, 13 borehole sites provided data of sufficient quality to extract MAGT and ALT as described below.

MAGT represents the mean annual ground temperature at the depth of zero annual temperature amplitude. For each site, we examined its daily temperature profiles to identify this depth, which was approximated as the depth where the difference between the maximal and minimal daily temperatures over a year was less than 0.15 °C. When no depth satisfied this criterion, the deepest available measurement depth was used as a proxy of zero-amplitude depth. At several sites where the deepest depth had to be used, the recorded daily temperatures exhibited unusually large fluctuations throughout the year that are inconsistent with expected thermal conditions at depth, indicating potential issues with the thermistor logger. These sites were excluded from our analysis.

ALT is determined as the annual maximum depth of the 0°C isotherm, calculated by linear interpolation of the freezing points within the daily thermal profiles across the year. Only days for which the shallowest sensor exceeded 0°C and a positive-to-negative temperature crossing was present were considered valid.

Table 1 summarizes the MAGT and ALT that we extracted at the 13 borehole sites, including their multi-year averages and the linear trends. The “Borehole PTI” represents the PTI rank derived from the extracted MAGT and ALT data at each site. It follows the same two-tier ranking scheme described in the manuscript. Based on their geographic locations, these sites can be broadly grouped into three regional clusters: Labrador–Ungava Bay in the east, East Hudson Bay in the west, and Baffin Island in the north.

At the sites on Baffin Island, East Hudson Bay and Labrador coast, the borehole PTI values generally agreed with our predicted PTI at the 1<sup>st</sup>-tier level, although shifts of one class within the 2<sup>nd</sup>-tier were observed at several sites. The high-latitude sites at Baffin Island indicated relatively stable permafrost (borehole PTI of 11 and 12), while those at East Hudson Bay exhibited lower stability (borehole PTI of 22). The two southernmost sites, UMIROCA at East Hudson Bay and KANGCRE along the Labrador coast, showed the most vulnerable permafrost in this region (borehole PTI of 31).

Both Way et al. (2018) and Wang et al. (2023) reported that permafrost along the Labrador Coastline was underestimated and may be more resilient than suggested by existing permafrost maps. As highlighted in bold in Table 2, the borehole PTI at all four sites at Ungava Bay are one class lower in the 1<sup>st</sup>-tier ranking than our predicted PTI, i.e., cool permafrost at borehole sites while our MAGT product indicated warm permafrost. This consistent discrepancy suggests that ground temperatures in the region may be systematically overestimated in global permafrost products, leading to an underrepresentation of permafrost stability along the Labrador coastline. It should be noted, however, that peatland permafrost along the Labrador coast is relatively narrow and limited in spatial extent. The observed biases likely reflect the influence of local environmental conditions that cannot be fully captured by global satellite-derived products.

**Table 1.** Summary of the 13 Nordicana D8 borehole sites used in this analysis. The table is provided solely to support our response.

Site ID	Lat (°)	Long (°)	Years	max depth (m)	MAGT (°C)	MA GT trend	ALT (m)	ALT trend	Bore hole PTI	Pred icted PTI
BYLOTPP	73.156	-79.959	2001-11	11	-11.13	Yes	0.92	No	12	12

Baffin Island	PAN02TC	66.155	-65.671	2010-15	14.9	-6.63	Yes	1.53	No	12	11
	PAN01TC	66.151	-65.688	2010-15	13.85	-3.29	Yes	2.44	No	12	11
	IQAV2TC	63.754	-68.546	2011-13	15	-4.11	No	1.48	No	11	11
	IQAV3TC	63.747	-68.522	2011-16	14.7	-3.36	No	1.54	No	11	11
Ungava Bay	QUAQ156	61.044	-69.614	2005-22	19.56	-3.15	Yes	6.47	No	<b>12</b>	<b>21</b>
	AUPA299	59.299	-69.600	2004-22	19.1	-2.38	Yes	1.73	No	<b>22</b>	<b>32</b>
	TSJQ157	58.700	-69.917	2002-20	20	-1.58	Yes	5.47	No	<b>22</b>	<b>32</b>
	TSJQ304	58.700	-69.952	2000-21	11	-2.87	Yes	2.33	Yes	<b>23</b>	<b>32</b>
Labrador Sea	KANGCRE	58.694	-65.939	2008-22	20	-0.27	No	3.80	No	31	32
East Hudson Bay	AKUL162	60.817	-78.155	2009-21	9.5	-2.81	Yes	2.46	No	22	21
	PUVIREF	60.057	-77.287	2006-21	3.75	-2.24	Yes	2.00	Yes	23	21
	UMIROCA	56.542	-76.522	2004-20	20	-0.19	No	15.43	No	31	31

The comparisons presented Fig.2 and Table 2 highlight the need of further investigation in peatlands. In particular, the derivation of MAGT in peatland permafrost may require refinement to account for the uniquely large thermal offset, as described in your previous studies. Actually, we also explored the peatland product in our study. However, the currently available global peatland product (Global Peatland MAP–GPM v2) is quite coarse, and contains only two broad classes: peat dominated, and peat in soil mosaic. As a result, may coastal peatland complexes, including those along Ungava Bay and Labrador Coastlines, are not explicitly identified. Limited by data quality, our study suggested that peatland did not exert a significant influence on PTI distribution. With fine-scale peatland product available in the future, it will become possible to better evaluate the thermal regimes of peatland permafrost at regional and global scales.

#### Proposed revision in manuscript:

We will strengthen our uncertainty assessment of the predicted PTI by adding these Nordicana D8 borehole sites into our ground-observation dataset. The original figure (Fig.10) will be revised accordingly to reflect the expanded analysis. The corresponding descriptions, methodology, and dataset reference will also be included in the manuscript.

In addition, Table 1 will be expanded to include all in-situ monitoring stations used in our evaluation, including sites from GTN-P, CALM, Nordcana D8, and other relevant datasets identified through further literature review. This comprehensive inventory of evaluation sites will be provided in the Appendix.

#### New references:

- Allard, M., Sarrazin, D., L'Herault, E. 2024. Borehole and near-surface ground temperatures in northeastern Canada, v.1.6.0. Nordicana D8. [10.5885/45291SL-34F28A9491014AFD](https://doi.org/10.5885/45291SL-34F28A9491014AFD)
- Way, R.G., and Lewkowicz, A.G. 2016. Modelling the spatial distribution of permafrost in Labrador–Ungava using the temperature at the top of permafrost. *Canadian Journal of Earth Sciences*, 53(10): 1010–1028. doi:10.1139/cjes-2016-0034.

- Way, R.G., Lewkowicz, A.G., and Zhang, Y. 2018. Characteristics and fate of isolated permafrost patches in coastal Labrador, Canada. *The Cryosphere*, 12(8): 2667–2688. doi:10.5194/tc-12-2667-2018.
- Wang, Y., Way, R.G., Beer, J., Forget, A., Tutton, R., and Purcell, M.C. 2023. Significant underestimation of peatland permafrost along the Labrador Sea coastline in northern Canada. *The Cryosphere*, 17(1): 63–78. doi:10.5194/tc-17-63-2023.

Sincerely,  
Dianfan Guo, Cuizhen Wang, and Shuying Zang