

### General assessment

5 This manuscript presents an extensive and carefully executed field study of wintertime CO<sub>2</sub> and CH<sub>4</sub> fluxes in Arctic tundra using high-resolution snowpack gas concentration gradients. The dataset is unusually rich in spatial coverage for winter conditions, and the combination of snow microstructure measurements (SMP) with gas concentration profiles represents a clear methodological strength. The paper addresses an important and timely topic for **Biogeosciences**, namely the quantification and spatial variability of cold-season greenhouse gas fluxes and their implications for model parameterisation. The manuscript is generally well written, logically structured, and supported by appropriate statistical analyses. The results  
10 provide valuable insights into (i) the role of snow depth and soil temperature in controlling winter CO<sub>2</sub> emissions, (ii) the occurrence of wintertime CH<sub>4</sub> uptake in forested tundra, and (iii) the limited influence of vertical snow microstructure on diffusive flux estimates.

However, some key interpretations require further clarification and, in a few cases, stronger justification. In particular, the discussion of winter CH<sub>4</sub> uptake, the assumption of steady-state diffusion and linear gradients, and the broader implications  
15 for process representation in terrestrial biosphere models would benefit from additional nuance. This study represents a valuable contribution to the understanding of winter greenhouse gas fluxes in Arctic tundra and is well suited for **Biogeosciences**. The literature cited is adequate and so are the graphics. I suggest a minor revision of the manuscript according to my specific comments before to consider it for publication on the Journal. After addressing the points above—particularly regarding the interpretation of CH<sub>4</sub> uptake and the limits of methodological generalisation - I recommend its publication.

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### Response

We thank the referee for the thorough and constructive assessment and for recognising the methodological strengths, dataset quality, and relevance of the study. We address the specific comments below.

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## Specific comments

The observation of consistent net CH<sub>4</sub> uptake in the forested transect (T4-Forest) under frozen conditions is one of the most interesting results of the study, but it also requires a more cautious interpretation. While the authors correctly cite recent evidence of winter CH<sub>4</sub> sinks in Arctic and sub-Arctic environments, CH<sub>4</sub> uptake is more commonly reported during the growing season or shoulder seasons, when liquid water availability and oxygen diffusion are less constrained.

The manuscript would benefit from a clearer discussion of the mechanisms enabling methanotrophic activity at soil temperatures between approximately -6 and 0 °C.

In particular:

- The possible role of zero-curtain conditions should be discussed more explicitly, including whether soil temperature measurements at the snow–soil interface are sufficient to infer liquid water availability in the upper soil layers.
- Alternative explanations, such as net uptake driven by diffusion-limited emissions rather than active oxidation, should be acknowledged and discussed.
- The comparison with summer or shoulder-season CH<sub>4</sub> uptake rates reported in the literature (including sites with similar vegetation and soil types) could be strengthened to contextualise the magnitude of the observed winter sink.

## Response

We thank the reviewer for their insightful comments regarding the interpretation of the consistent net CH<sub>4</sub> uptake observed in the T4-Forest transect. We agree that the persistence of a methane sink under frozen conditions warrants a more detailed discussion of the underlying physical and biological mechanisms, particularly concerning liquid water availability and the distinction between active oxidation and diffusion-limited processes. We have significantly expanded Section 4.1 to address these points as follows:

### Role of zero-curtain conditions and the sufficiency of soil-snow interface measurements

We have expanded the discussion to explicitly address the thermodynamic mechanisms (latent heat release and zero-curtain conditions) that allow liquid water to persist in frozen soil matrices. We also acknowledge that interface temperatures are a conservative proxy for the thermal state of deeper soil layers, where microbial activity likely continues.

#### *Revised manuscript text (Discussion)*

*Near-zero basal temperatures at T4-Forest suggest that much of the near-surface soil profile likely remained at zero-curtain temperature conditions, When soil temperatures are poised near 0 °C due to release of latent heat during the phase transition of water to ice, allowing liquid water content and ice to coexist in soil pore space (Devoie et al., 2022; Tucker, 2014; Outcalt et al., 1990). Remaining liquid soil water over winter sustains microbial metabolic activity in thin films surrounding soil particles even at temperatures as low as -18 °C (Dutch et al., 2024; Elberling and Brandt, 2003; Sullivan et al., 2008).*

Northern boreal forest  $CH_4$  uptake rates have been reported to be within the same order of magnitude as those found in T4-Forest, where soils also remained in zero-curtain conditions throughout winter (Lee et al., 2023; Mavrovic et al., 2025). Evidence for microbial  $CH_4$  consumption within the T4-Forest is provided by the significant inverse relationship between  $F_{CO_2}$  and  $F_{CH_4}$  (**Error! Reference source not found.**). This inverse relationship aligns with global patterns where winter  $CO_2$  emissions explain nearly 96% of the variability in  $CH_4$  oxidation, effectively serving as a proxy for the biological activation and oxygen diffusion required for substrate consumption (Kim et al., 2021; Voigt et al., 2023). High-affinity methanotrophs likely maintain this activity in the aerobic upper soil layers during mid-winter; however, the preferential coupling of basal temperatures with  $CO_2$  rather than  $CH_4$  flux magnitudes suggests that  $CH_4$  consumption may also take place in deeper, relatively warmer soil layers (Donateo et al., 2025; Mikan et al., 2002b). Further variability in  $CH_4$  uptake magnitudes could also be explained by oxygen, and the liquid portion of soil moisture available in upper soil horizons have been identified as important regulators of uptake (D'Imperio et al., 2023; Lee et al., 2023; Rößger et al., 2022). However, soil temperature measurements taken at the soil-snow interface may be insufficient to infer liquid water availability across the upper soil layers. As the active layer typically freezes faster from the surface downward due to large soil-atmosphere thermal gradients, interface temperatures may drop below ideal temperatures for microbial activity, while deeper carbon-rich layers remain in a zero-curtain state for weeks or months longer (Pedron et al., 2022; Yi et al., 2020). Relying solely on surface temperatures contributes to the cold-soil temperature biases in carbon fluxes observed in terrestrial biosphere models such as CLM5.0, which often fail to resolve the extended duration of these subsurface thermal refugia and resulting non-growing season carbon losses (Damseaux et al., 2025; Dutch et al., 2024; Tao et al., 2021).

#### **Alternative explanations: diffusion-limited emissions vs. active oxidation**

We have incorporated the concept of physical encapsulation and diffusion-limited transport as alternative explanations for observed net uptake, particularly in saturated landforms where basal ice may occlude gas efflux. We contrast this with evidence of active oxidation in better-drained transects, as indicated by the coupling of  $CO_2$  and  $CH_4$  fluxes.

#### ***Revised manuscript text (Discussion)***

Alternatively observed net  $CH_4$  uptake in saturated landcovers may be limited by physical encapsulation of soil layers by ice, where basal ice or thick frozen soil layers creates an impermeable barrier occluding efflux of  $CH_4$  produced in deeper, unfrozen soil horizons (Elberling and Brandt, 2003; van Bochove et al., 2001). Such diffusion-limited transport, exacerbated by the occlusion of soil pores by ice, can decouple subsurface  $CH_4$  production from soil-atmosphere exchange, potentially resulting in apparent uptake signals if atmospheric  $CH_4$  is consumed in the uppermost aerated soil or if production is physically trapped at depth (Mavrovic et al., 2025; Treat et al., 2018; Schimel et al., 2006). Slower  $CH_4$  diffusion through ice-filled pores in frozen soils can further mask the temperature dependence of winter  $CH_4$  fluxes, suggesting that surface net uptake may reflect a lack of transport from deeper source layers rather than high methanotrophic potential (Mavrovic et al., 2025).

Consequently, the fine-scale variability at T5-Inlet likely reflects a gradient where some microsites maintain active methanogenesis while others are governed by the passive trapping of greenhouse gases within the soil profile.

## 95 Comparison with summer and shoulder-season uptake rates

To contextualize the magnitude of the winter sink, we have integrated comparisons with local peak-summer automated chamber data and regional non-growing season datasets from Svalbard, Norway, and Greenland.

### *Revised manuscript text (Discussion)*

100 Consistent net uptake measured in the T4-Forest transect between -6 and 0 °C reveals that high-latitude forested soils can function as significant net sinks even under frozen conditions, representing an integrated balance of diffusive transport and microbial methanogenic and methanotrophic turnover within soils (Mast et al., 1998). Few measurements of wintertime CH<sub>4</sub> uptake specific to land surface types have been reported in high-latitude tundra environments, mainly due to the historical difficulty of resolving low-magnitude fluxes through Arctic snowpacks. Recent studies have begun to address this gap, with  
105 winter CH<sub>4</sub> uptake rates in northern closed-crown boreal forest uplands recently reported at  $-0.43 \pm 0.34$  to  $-0.47 \pm 0.26$  mg C m<sup>-2</sup> d<sup>-1</sup> (Mavrovic et al., 2025). For comparison, our observed winter forest uptake ( $-0.04$  to  $0.08$  mg C m<sup>-2</sup> d<sup>-1</sup>) represents a persistent, albeit diminished sink relative to peak growing season consumption. At TVC, automated chambers have recorded summer CH<sub>4</sub> uptake rates for lichen and shrub communities between  $-0.37$  and  $-0.44$  mg C m<sup>-2</sup> d<sup>-1</sup> (converted from  $-0.49$  to  $-0.59$  mg CH<sub>4</sub> m<sup>-2</sup> d<sup>-1</sup>), suggesting winter forest uptake magnitudes are roughly one order of magnitude lower than peak summer  
110 rates in the same region (Voigt et al., 2023).

Landscape-scale tundra winter CH<sub>4</sub> sinks have also been observed in Svalbard, Greenland, and Norway, where soil organic layers are less spatially pervasive than in TVC (D'Imperio et al., 2023; Donateo et al., 2025; Treat et al., 2018). In Svalbard's dry upland tundra, median CH<sub>4</sub> fluxes remain negative throughout the winter, ranging from  $-0.18$  to  $-0.37$  mg C m<sup>-2</sup> d<sup>-1</sup> (reported as  $-0.17$  to  $-0.36$  nmol m<sup>-2</sup> s<sup>-1</sup>), while notable net uptake events during the freezing shoulder season can reach  $-0.72$   
115 mg C m<sup>-2</sup> d<sup>-1</sup> ( $-0.69$  nmol m<sup>-2</sup> s<sup>-1</sup>) (Donateo et al., 2025). Growing season and start-of-cold-season CH<sub>4</sub> uptake measured at TVC across drier landforms, including upland tundra and polygonal rims, further suggest that methanotrophic activity persists long after plant senescence (Ivanova et al., 2025; Voigt et al., 2023). The magnitude of this winter sink is particularly important when contrasted with comparatively wetter tundra sites in Northern Alaska, where summer emissions from even relatively dry polygon rims can range from  $4.5$  to  $9.6$  mg C m<sup>-2</sup> d<sup>-1</sup> (McEwing et al., 2015). Comparisons between different pan-Arctic land  
120 covers highlight that while mid-winter CH<sub>4</sub> uptake may be a small component of the annual budget, persistence of aerobic oxidation in well-drained forested and upland soils provides a non-negligible offset to winter CH<sub>4</sub> emissions from saturated hotspots.

The flux calculations rely on the assumption of steady-state conditions and linear concentration gradients through the snowpack. While the authors demonstrate that most concentration profiles are well approximated by linear fits, some profiles exhibit clear departures from linearity and partial homogenisation in the basal snow layers. In this context, the manuscript would benefit from a clearer justification of the steady-state assumption, particularly considering potential sources of short-term temporal variability such as wind pumping, transient pressure fluctuations, or diurnal temperature changes. In addition, a brief sensitivity analysis, or at least a qualitative discussion, of how deviations from linearity could bias flux estimates would strengthen the robustness of the results, especially in low-flux environments such as the T3-Tussock transect where gradients are often weak.

## Response

We acknowledge that the validity of a two-point sampling approach is dependent upon the maintenance of a linear diffusive regime. We have updated the manuscript to clarify that this simplification is intended for stable, mid-winter conditions where the snowpack acts as a uniform porous medium and should not be applied to snowpacks containing significant impermeable ice layers or those undergoing active melt-freeze cycles. We have also explicitly stated reported uncertainty bounds for  $F_{CO_2}$  and  $F_{CH_4}$  (Figures 5 and 6) incorporate the standard error of the linear regression slopes used to calculate  $dC/dz$ , thereby providing a robust statistical account of the variance induced by profile non-linearity. Furthermore, we have expanded our discussion to address specific scenarios where snowpack stratigraphy may result in biased flux calculation.

### *Revised manuscript text (Methods)*

*Flux estimates assume quasi-steady-state diffusive transport and linear concentration gradients through the snowpack. To ensure the validity of this assumption and minimize confounding effects of turbulent wind pumping or rapid barometric pressure fluctuations, all measurements were conducted during stable meteorological conditions, characterized by wind speeds below  $3.5 \text{ m s}^{-1}$ .*

### *Revised manuscript text (Discussion)*

*Non-linear departures in snowpack gas concentration profiles, particularly homogenization of gas concentrations observed in basal depth hoar layers, introduce a known potential for gradient underestimation (Dutch et al., 2022). Such concentration gradient ( $dC/dz$ ) underestimations, particularly in low carbon flux environments such as the T3-Tussock transect, may reflect a reduced concentration change over the sampled depth, resulting in  $F_{CO_2}$  and  $F_{CH_4}$  magnitudes that are lower than the actual soil metabolic flux rates. Wind-induced advection (wind pumping) can further perturb gradients in the upper snow strata, although these effects are often transient and confined to periods of high barometric instability (Jones et al., 1999a; Dutch et al., 2024; Mavrovic et al., 2025).*

*Previous studies have also identified non-linear profiles in snowpack GHG distributions when impermeable soil layers were present (van Bochove et al., 2001). In such cases, using snowpack basal concentrations would likely overestimate*

instantaneous flux magnitudes, and would affect estimates in the timing of emissions rather than seasonal budget estimates. While profiles at TVC were predominantly linear, significant gas trapping below frozen soil barriers can artificially increase concentration gradients once released through thermal or mechanical cracking, or conversely, mask subsurface production entirely (Jones et al., 1999a). Such diffusion-limited transport decoupling suggests that measurements taken strictly within the snowpack may periodically reflect physical encapsulation rather than active biological oxidation (Elberling and Brandt, 2003; van Bochove et al., 2001).

The application of Fickian diffusion models to wintertime greenhouse gas exchange assumes linear concentration gradients through the snowpack. Uncertainty bounds (**Error! Reference source not found.** and **Error! Reference source not found.**) incorporate the standard error associated with linear regression of concentration versus depth, accounting for variance introduced by non-linear yet significant vertical profile concentration gradients.

Finally, further clarification is needed on how profiles with weak or non-significant concentration gradients were handled in the flux calculations and in the subsequent upscaling and subsampling analyses.

### **Response**

We have clarified this explicitly in the Methods.

*Revised manuscript text (Methods)*

*Profiles exhibiting non-significant concentration gradients ( $p > 0.05$ ) were excluded from subsampling and scaling analyses to avoid introducing noise from profiles indicating negligible net exchange. These profiles were interpreted as representing near-zero flux conditions for the corresponding sampling period.*

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The finding that reliable flux estimates can be obtained using only basal and near-surface gas concentrations is potentially very impactful and could significantly simplify future field campaigns. However, this conclusion may be partly site- and condition-specific and would benefit from additional clarification. In particular, it would be helpful to specify the environmental conditions under which this simplification is expected to remain valid, such as the absence of ice layers, predominantly dry snowpacks, or limited melt–freeze cycles. Further discussion is also warranted on whether this approach can reasonably be extended to wetter snowpacks, profiles dominated by ice crusts, or sites experiencing mid-winter thaw events, where diffusive transport may deviate from the assumptions applied here.

## **Response**

We have updated the Discussion to delineate the specific environmental boundaries of the two-point sampling approach, clarifying that its robustness is contingent upon maintaining a linear diffusive regime in dry, cold snowpacks free of stratigraphic barriers. The revised text now explicitly addresses these features, thereby better framing the applicability of this simplified methodology.

*Revised manuscript text (Discussion)*

*Agreement between full-profile fluxes and estimates derived from basal and near-surface concentrations appears robust under the predominantly dry, cold snowpack conditions encountered during this study. This simplification is likely to remain valid in where snowpacks lack extensive ice layers and experience limited mid-winter melt-freeze cycles, allowing molecular diffusion to remain the dominant transport mechanism. In wetter snowpacks or during episodic thaw events, diffusive transport may deviate from linear assumptions as liquid water occludes pore spaces and promotes the formation of ice lenses that may decouple subsurface microbial production from surface exchange (Elberling and Brandt, 2003; Mavrovic et al., 2023). Soil stratigraphic barriers or basal ice can trap produced gases at depth, potentially leading to zero-gradient signals within the overlying snow despite ongoing soil metabolic activity (Jones et al., 1999; van Bochove et al., 2001). Consequently, while a two-point sampling approach offers a viable and efficient method for regional winter carbon budget mapping, its application must be restricted to stable meteorological windows and sites free of discrete physical barriers to diffusive flux.*

The manuscript frequently refers to implications for TBMs, but these links remain somewhat conceptual. The paper would be strengthened by a more explicit discussion of:

- 210 • Which specific model parameters (e.g. winter soil respiration temperature sensitivity, snow thermal conductivity, CH<sub>4</sub> oxidation schemes) are most directly informed by the presented data.
- How the observed fine-scale spatial variability could realistically be represented or parameterised at the grid-cell scale used in Earth system models.

### Response

215 We have expanded the Discussion to more explicitly identify model parameters informed by our results and to clarify how fine-scale variability could be represented at model grid scales.

### *Revised manuscript text (Discussion)*

220 *This is particularly relevant to upscaling small-scale fluxes from tens of metres to scales typically used in Terrestrial Biosphere Models (TBMs), where finer-scaled data is aggregated by averaging discrete data points to much larger grid cells (Levy et al., 2022).*

225 *Measurements from TVC can directly inform TBMs by providing high-resolution empirical bounds for temperature sensitivity ( $Q_{10}$ ) of cold-season biogeochemical processes as a primary source of uncertainty in Arctic carbon simulations (Dutch et al., 2024). The relationship between late-winter soil temperature, snow depth, and  $F_{CO_2}$  suggests that deterministic models using grid-cell mean snow depths likely underestimate winter activity by failing to capture the disproportionate contribution of  $F_{CO_2}$  from warmer frozen soils under deeper snow. Our findings suggest that bulk snowpack diffusivity remains a robust approximation for models, provided that refined snow thermal conductivity parameterizations are implemented to correct the cold soil temperature biases that currently inhibit accurate flux simulations. A need for revised temperature-response curves in Arctic tundra extends to CH<sub>4</sub> dynamics; where persistent uptake observed in the forested transects indicates that current*

230 *TBM methane production and oxidation schemes require better low temperature calibration to account for microbial oxidation occurring at soil temperatures below 0 °C. Following the process-based evaluation by Dutch et al., (2024), which highlighted how default model configurations often simulate near-zero winter fluxes at TVC due to overly restrictive soil moisture thresholds ( $\Psi_{min}$ ) and respiration temperature responses, a transition is recommended toward sub-pixel distribution-based parameterizations (e.g., probability density functions) that can represent sub-grid heterogeneity in snow insulation and soil*

235 *thermal regimes.*

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