CC1: "Comment on egusphere-2025-5637" – Jeff Welker (28 Nov 2025)

Gabriel, great job on this and thanks so much for continuing to focus on winter emissions so so important.

Response

We thank Jeff Welker for his positive assessment of the manuscript and for underscoring the importance of winter greenhouse gas fluxes to Arctic carbon fluxes.

However, you have missed my program's beginning of this modern day (past ~ 3 decades) field of research which was initially criticized when I presented our initial NSF funded data from Arctic Alaska in CPH at the 1997 ITEX meeting. I showed the flux data, measurable and argued that when winter emissions (~240 days of snow cover in N AK) were added to summer net fluxes, the tundra was a net C source: "Jeff you are crazy". how can all that SOM, permafrost be present if the system is a net C source ?" came the audience challenges. My reply was today is different than the past and we now have real emission data from what makes the Arctic, the Arctic, winter. I have been delighted see Webb, Natalie, and others, including your team, join my winter emission crusade.

Response

We thank Jeff Welker for drawing attention to this important omission. We agree that the pioneering winter flux measurements led by the Welker group in the late 1990s and early 2000s constitute foundational contributions to modern understanding of Arctic winter carbon exchange. We have revised the Introduction to explicitly acknowledge these earlier studies and to situate our work within this established research trajectory.

Revised manuscript text (Introduction)

Simulations urgently require improvement as measurements of cold season GHG fluxes in Arctic ecosystems have been shown to contribute substantially to annual carbon budgets. Field measurements from northern Alaska demonstrated that CO_2 emissions during the snow-covered season can be large enough to offset or exceed growing-season uptake (Fahnestock et al., 1998, 1999; Jones et al., 1999b; Welker et al., 2000), and recent syntheses reinforce these findings at pan-Arctic scales (Natali et al., 2019; Rafat et al., 2021). Relatively small CH_4 emissions during the lengthy cold season have also been shown to contribute >50 % of annual total sources in Alaskan tundra (Zona et al., 2016). Collectively, such studies established winter as a critical period for Arctic carbon cycling and motivated subsequent efforts to quantify cold-season fluxes across a wider range of Arctic and sub-Arctic ecosystems.

Revised manuscript text (Introduction)

Soil-atmosphere fluxes derived from direct measurements of snowpack CO_2 and CH_4 concentrations and steady-state diffusion models have been used for several decades to estimate winter greenhouse gas fluxes in Arctic ecosystems. Manually extracting air from snowpacks with syringes allows for cost effective and spatially distributed flux measurements. However, large sample sizes (n >10) are difficult to collect within time scales where meteorological conditions are stationary and wind speeds are low, and require several samples to be extracted and analysed per microsite for flux calculations (Jones et al., 1999a; Mavrovic et al., 2023; Seok et al., 2009; Zhu et al., 2014). Faster, high accuracy in situ snowpack gradient measurements of CO_2 flux (and later CH_4) were more recently made possible using portable Infrared Gas Analysers (IRGA), quantifying winter soil-atmosphere fluxes across a variety of Arctic land surface covers (Fahnestock et al., 1998; Jones et al., 1999b; Pirk et al., 2016).

These are some of the absolute foundational papers that you should be including in your introduction of the "issue" and in the discussion as to how this data compare to what the Welker program discovered decades ago and continue today. Thank you for all that you and your team are doing but knowing and recognizing the origins of this research theme, is essential to educating the readers on the foudational science and how your new science continues to strengthen our understanding of 2/3 of the Arctic's calendar :)

The first 4 are in many ways the "beginning of the modern winter C emission studies initiated by my team/s", W Ochel's group also published a 1997 paper as well.

And, our continued contributions with packages like Natali et al. 2019

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Kantola, N., **Welker, J. M.**, Leffler, A. J., et al. (2025) Impacts of winter climate change on northern forest understory carbon dioxide exchange determined by reindeer grazing. *Science of the Total Environment*. doi.org/10.1016/j.scitotenv.2025.180089

Response

We agree and have incorporated the cited literature into the discussion. Several of these studies directly inform interpretation of our winter CO_2 flux magnitudes, snow depth controls, and the role of winter processes in annual carbon budgets.

Revised manuscript text (Discussion)

Measured winter CO_2 flux magnitudes at TVC are consistent with early observations from Arctic Alaska showing sustained cold-season emissions under snow cover (Fahnestock et al., 1998, 1999; Jones et al., 1999b; Welker et al., 2000). Subsequent work has demonstrated that snow depth, thermal insulation, and active-layer dynamics exert strong controls on winter respiration and the age of respired carbon (Lupascu et al., 2018; Pedron et al., 2023; Schimel et al., 2006; Sullivan et al., 2008). Measurements at TVC extend these findings by resolving fine-scale spatial variability in winter fluxes and by evaluating how simplified sampling strategies capture this variability under dry snowpack conditions.

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RC1: "Comment on egusphere-2025-5637" – Anonymous Referee #1 (17 Dec 2025)

General assessment

This manuscript presents an extensive and carefully executed field study of wintertime CO_2 and CH_4 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 provide valuable insights into (i) the role of snow depth and soil temperature in controlling winter CO_2 emissions, (ii) the occurrence of wintertime CH_4 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_4 uptake, the assumption of steady-state diffusion and linear gradients, and the broader implications 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_4 uptake and the limits of methodological generalisation - I recommend its publication.

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.

Specific comments

The observation of consistent net CH_4 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_4 sinks in Arctic and sub-Arctic environments, CH_4 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_4 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_4 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_{CO2} and F_{CH4} (**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.

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)

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_4 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 winter CH_4 uptake rates in northern closed-crown boreal forest uplands recently reported at -0.43 ± 0.34 to -0.47 ± 0.26 mg C m^{-2} d^{-1} (Mavrovic et al., 2025). For comparison, our observed winter forest uptake (-0.04 to 0.08 mg C m^{-2} d^{-1}) represents a persistent, albeit diminished sink relative to peak growing season consumption. At TVC, automated chambers have recorded summer CH_4 uptake rates for lichen and shrub communities between -0.37 and -0.44 mg C m^{-2} d^{-1} (converted from -0.49 to -0.59 mg CH_4 m^{-2} d^{-1}), suggesting winter forest uptake magnitudes are roughly one order of magnitude lower than peak summer rates in the same region (Voigt et al., 2023).

Landscape-scale tundra winter CH_4 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_4 fluxes remain negative throughout the winter, ranging from -0.18 to -0.37 mg C m^{-2} d^{-1} (reported as -0.17 to -0.36 nmol m^{-2} s^{-1}), while notable net uptake events during the freezing shoulder season can reach -0.72 mg C m^{-2} d^{-1} (-0.69 nmol m^{-2} s^{-1}) (Donateo et al., 2025). Growing season and start-of-cold-season CH_4 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^{-2} d^{-1} (McEwing et al., 2015). Comparisons between different pan-Arctic land covers highlight that while mid-winter CH_4 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_4 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_{CO2} and F_{CH4} (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 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_{CO2} and F_{CH4} 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.

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:

- Which specific model parameters (e.g. winter soil respiration temperature sensitivity, snow thermal conductivity, CH_4 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

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)

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).

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_{CO2} suggests that deterministic models using grid-cell mean snow depths likely underestimate winter activity by failing to capture the disproportionate contribution of F_{CO2} 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_4 dynamics; where persistent uptake observed in the forested transects indicates that current 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 (Ψ_{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 thermal regimes.

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RC3: Anonymous Referee #2, "Comment on egusphere-2025-5637" (22 July 2026)

General assessment and major methodological comment

Gosselin and others use gradient measurements to estimate carbon dioxide and methane flux through snow. Methane fluxes in this instance are a bit of a novelty. My biggest concern is the lack of inclusion of advection, also called 'enhanced diffusion' from snow following the fundamental contributions of Bowling, Massman and others. These will be of particular importance in characteristically windy conditions owing to what is often called 'pressure pumping' and the Venturi effect. This is alluded to on line 63 but excluded from equation 1. From the review and comment history note that many of the papers from the Welker group also make this mistake. These major methodological concerns should be addressed in the revision and the following minor comments considered.

Response

We thank the referee for constructive feedback on advective transport from Equation 1 and for directing us to the foundational contributions of Bowling, Massman, and colleagues. We agree that wind pumping has the potential to add a non-diffusive component to snowpack gas transport, and we now represent it explicitly through an effective diffusivity enhancement factor, $D_{eff} = (1 + \varepsilon)\varphi\tau D$, where ε is the fractional enhancement of the diffusion coefficient by non-diffusive transport. We adopt this form, rather than a separate mean advective term because turbulent and barometric pressure pumping is oscillatory with near-zero mean flow, so its net effect is a dispersive enhancement of diffusion rather than a sustained advective flux (Massman et al., 1997; Colbeck, 1997; McDowell et al., 2000; Seok et al., 2009; Bowling and Massman, 2011; Rains et al., 2016; Graham and Risk, 2018). Quasi-static (Venturi) advection, which does produce a mean flow, requires sustained pressure fields over pronounced topography and is minimal on the low-relief terrain sampled. We bound ε for our sampling conditions, show that it is near zero, and demonstrate that Equation 1 (the diffusive form, $\varepsilon = 0$) is the appropriate limit. We have revised the Methods and Discussion accordingly.

Enhancement-factor representation and choice of ε

We rewrote the transport formulation so that the non-diffusive contribution is explicit and reduces continuously to the diffusive case. The effective diffusivity Deff = (1 + ε)φτD carries all wind-pumping effects in the single dimensionless term ε, which is zero for pure diffusion and grows with snow surface wind speed, snowpack air permeability, and barometric variance (Massman et al., 1997; Bowling and Massman, 2011).

Bowling and Massman, (2011) measured ε rising from zero in calm air to 0.11 to 0.33 at a wind speed of 10 m s^{-1}, reaching up to about 0.40 during short (hours-long) high-wind episodes and 0.08 to 0.11 when integrated over a full winter. Massman et al., (1997) modelled turbulence-driven pressure pumping at a subalpine meadow with mean in-meadow wind speeds of 1 to 4 m s^{-1} (open-site winter mean about 10 m s^{-1}) and concluded that, unless it alters the snowpack boundary concentrations, pressure pumping does not appreciably enhance through-snowpack diffusion. The 1 to 4 m s^{-1} regime in which that model found a minor effect encompasses our upper 3.5 m s^{-1} sampling threshold. Restricting sampling to wind speeds below 3.5 m s^{-1} therefore places ε well below the wind speed where pressure pumping of gases through the snowpack becomes influential. Snowpack concentration profiles collected during the campaign also provide an empirical bound as fluxes from two near-boundary samples matched full-profile fluxes (Figure. 7), and a wind-varying ε large enough to matter would disrupt the upper portion of the near 1:1 gas flux gradient (R^2 = 0.994 to 0.998) presented.

In addition, a separate study of continuous measurements at the same site show wind events dilute the snowpack profile only transiently, and that the diffusive gradient re-establishes within hours once wind subsides, consistent with the diffusive re-equilibration time of the snowpack (Dutch et al., 2026). Atmospheric mixing is therefore a short-lived perturbation rather than a persistent transport mode. Sampling in stable, low-wind windows, and not in the hours immediately following a wind event, therefore corresponds to ε tending to zero and the enhancement term drops from Equation 1. This same-site evidence is provisional (preprint) and is used here only to support the choice of sampling windows; it is not relied upon in the manuscript revision.

Revised manuscript text (Methods section 2.1)

Non-diffusive transport driven by wind pumping is represented through an effective diffusion coefficient altering equation 1 to:

$$F_{gas} = -(1+\varepsilon)\varphi\tau D\left(\frac{dC}{dz}\right)N_a \quad (6)$$

where ε is a dimensionless enhancement factor that is zero for pure molecular diffusion and increases with snow-surface wind speed, snowpack air permeability, and barometric variance (Massman et al., 1997; Bowling and Massman, 2011).

Turbulent and barometric pressure pumping is oscillatory with near-zero mean flow, so its net effect is a dispersive enhancement of diffusion rather than a mean advective flux (Massman et al., 1997; Bowling and Massman, 2011), whereas quasi-static (Venturi) advection depends on the wavelength and height of surface relief such as sastrugi or drifts and on the resulting surface pressure perturbation (Colbeck, 1997; Massman et al., 1997). Bowling and Massman, (2011) directly measured ε with values reaching zero in calm air and up to 0.33 at a wind speed of 10 m s^{-1}. Modelling of a layered snowpack driven by such fluctuations at mean wind speeds of 1 to 4 m s^{-1} shows that pressure pumping does not appreciably enhance through-snowpack diffusion unless it alters the boundary concentrations (Massman et al., 1997). Furthermore, a lower-permeability surface layer such as a wind crust further attenuates the penetration of pressure-driven airflow into the pack (Colbeck, 1997). The advective enhancement is therefore bounded near zero (ε ≈ 0) under which conditions and the flux reduces to its diffusive form as Eq.(1) when wind speed is low, the snow surface lacks pronounced relief, and a wind crust is present.

Revised manuscript text (Methods section 2.3)

Flux estimates assume quasi-steady-state diffusive transport and linear concentration gradients through the snowpack, computed from the diffusive form of Equation 1 only. To ensure the validity of this assumption and satisfy the conditions under which the wind-pumping enhancement is negligible (section 2.1), all measurements were conducted during stable meteorological conditions, characterized by wind speeds below 3.5 m s^{-1}, and were restricted to microsites free of pronounced sastrugi or drift relief and capped by a wind crust free of ice lenses.

Revised manuscript text (Discussion section 4.2)

Wind-induced advection (wind pumping) can further perturb gradients in upper snow layers, although these effects are often transient and confined to periods of high wind speeds (Jones et al., 1999; Mavrovic et al., 2025), although those effects were negated in this study by sampling while wind speeds remained below 3.5 m s^{-1}.

Revised manuscript text (Discussion section 4.3)

We show no significant difference between calculating soil-atmosphere fluxes from basal snowpack CO_2 and CH_4 concentrations and ambient air above the snowpack, compared to calculations from a larger number of equally spaced samples throughout the snowpack. Together these findings reduce the measurement burden needed for rapid in situ instantaneous flux measurement, opening up potential for landscape-scale FCO_2 and FCH_4 winter budgets at larger spatial scales using remotely sensed snow properties while expanding measurement spatial coverage improving quantification of variability over a wider set of surface covers (Dutch et al., 2024; Ivanova et al., 2026; Virkkala et al., 2022).

Minor comments

L22: Regarding snow microstructure, were ice lenses present at any of the measurement sites?

Response

No ice lenses or discrete ice layers were observed at any microsite, as confirmed by high-precision SMP density profiles showing no sharp density spikes diagnostic of ice lenses. The absence of ice layers underpins the linear-diffusion assumption, because melt-refreeze ice lenses are the principal stratigraphic feature that decouples subsurface production from surface exchange. The reported observation in Results is improved, and we have added it to the discussion linking it to the validity of the diffusive formulation.

Revised manuscript text (Results)

Snowpacks were dry and free of discrete ice lenses or basal ice layers at all microsites throughout transects.

Revised manuscript text (discussion)

Robust agreement between full-profile fluxes and estimates derived from basal and near-surface concentrations was evident under the predominantly dry, cold snowpack conditions encountered at TVC. Where snowpacks lack extensive ice layers and experience limited mid-winter melt-freeze cycles, molecular diffusion will remain the dominant transport mechanism.

39: could also note methanotrophy (see also line 49)

Response

We agree. The Introduction previously framed warmer winter soils only as a source of CH_4. We have revised the text to state that net CH_4 exchange reflects the balance between microbial production and methanotrophic oxidation, both of which respond to soil temperature and to liquid-water and oxygen availability.

Revised manuscript text (Introduction)

As soil microbes are especially sensitive to temperature and to the availability of liquid soil moisture near and below freezing, warmer wintertime soils could alter emissions of potent greenhouse gases (GHGs) such as carbon dioxide (CO_2) and methane (CH_4) (Natali et al., 2019), with the direction of the net CH_4 response set by the balance between methanogenesis and methanotrophic oxidation under prevailing soil moisture and oxygen availability.

54: this is a long paragraph that covers many topics, including those only briefly mentioned like TBMs

Response

We agree and have divided the paragraph into two main topics. Paragraph 1: GHG flux uncertainties as represented by current TBMs. Paragraph 2: Current literature showing wintertime GHG fluxes have a significant effect on annual budgets.

59: soil microbial processes can be localized at far smaller spatial scales than that (e.g. dung)

Response

We have underlined the importance of smaller spatial scale features in the introduction. Fine scaled flux spatial variability is also addressed and described in the subsequent paragraph.

Revised manuscript text (Introduction)

However, eddy covariance flux systems aggregate fluxes at scales orders of magnitude larger than localised (<1 m^2) soil microbial processes, masking surface cover scale variability driven by localised conditions (i.e., soil temperature, available liquid soil moisture, labile nutrient availability, root zones, and discrete organic inputs such as faecal deposits).

109: why lower case co2 and ch4?

Response

The lowercase subscripts (D_{co2}, D_{ch4}, $D0_{co2}$, $D0_{ch4}$) were species labels rendered without correct formatting. We have corrected these to roman, non-italic chemical subscripts (D_{CO2}, D_{CH4}, $D_{0,CO2}$, $D_{0,CH4}$) throughout the equations and text.

123: don't use the star in formal mathematical equations

Response

We agree. We have removed the multiplication asterisk in the ice-density relation and replaced it with standard notation.

Revised manuscript text (Methods)

ρice = 0.9168 − 1 × 10-4 T (g cm-3; Haynes, 2016), where T is temperature in °C.

132: these have units

Response

We have added units to the standard diffusion coefficients and made the diffusion-coefficient units consistent between Equations 1 and 5. Standard values (Massman, 1998) are $D_{0,CO2}$ = 0.1381 $cm^2\ s^{-1}$ (1.381 × 10^{-5} $m^2\ s^{-1}$) and $D_{0,CH4}$ = 0.1952 $cm^2\ s^{-1}$ (1.952 × 10^{-5} $m^2\ s^{-1}$) at standard temperature and pressure.

188: if gas was pumped out, was it not returned so as not to create a vacuum and result in gas mixing within the snowpack?

Response

The LGR Ultra-Portable Greenhouse Gas Analyzer draws snowpack air through the probe by a fixed internal pump at approximately 0.8 standard L min^{-1} (~800 mL min^{-1}) and is a flow-through instrument, sampled air is vented to ambient air rather than returned to the snowpack. Three lines of reasoning indicate that extraction did not create a vacuum that mixed air within the profile.

1. The analyser reached a stable concentration plateau at each depth within approximately 60 s; a plateau under continuous extraction indicates that pore air arriving at the intake is replenished at constant composition from the surrounding layer, rather than measured concentrations drifting toward atmospheric values from progressive drawdown, and because snow is highly permeable the convergent intake flow is drawn isotropically from the adjacent pore space of the same layer.
2. The volume drawn per depth (~ 0.8 L over 60 s) is a few percent of the pore-air volume of the surrounding snow, of the order of tens of litres within a radius of at most 0.3 m from the intake at the measured porosities ($\varphi \approx 0.65$ to 0.78). Cumulative depletion is therefore limited to the volume within each vertical layer measured.
3. The extraction-induced mixing would flatten vertical gradients and drive replicate profiles apart, yet profiles were monotonic, reproducible across replicate profiles, and predominantly linear, and fluxes derived from two near-boundary samples agreed with full-profile fluxes to within $R^2 > 0.99$ (Figure 7); homogenisation was confined to the T3-Tussock transect, where near-atmospheric concentrations reflect near-zero flux rather than a sampling artefact. The manual snowpack gradient approach follows Mavrovic et al., (2023) and work from the Welker group.

Both Methods and Discussion were updated with these precisions.

Revised manuscript text (Methods)

Snowpack air was drawn to the analyser through a metal tube on a graduated avalanche probe by the instrument's fixed internal pump at approximately 0.8 standard L min^{-1}, and each depth was measured for approximately 60 s until CO_2 and CH_4 concentrations reached a stable plateau. The analyser is a flow-through instrument; sampled air was vented to ambient air rather than returned to the snowpack. The volume drawn per depth (~ 0.8 L over 60 s) is a few percent of the pore-air volume of the surrounding snow, of the order of tens of litres within a radius of at most 0.3 m from the intake at the measured porosities ($\varphi \approx 0.65$ to 0.78). Cumulative depletion was therefore limited to the volume within each vertical layer measured.

Revised manuscript text (Discussion)

Concentrations at distinct vertical sampling points concentration profiles were reproducible across replicate profiles and consistent between full-profile and two-point flux estimates (Figure 7), indicating that extraction did not draw down or homogenise air from different layers or ambient air.

Fig 2 is nice

Response

We thank the referee.

Fig 3: why combine all measurements to these plots when each would have a unique slope? The data themselves are extremely interesting so I can understand why you'd want to keep this from a demonstration point of view

Response

Individual per-microsite gradients were fitted separately and used for every flux calculation (Figures 4 to 8). We chose to aggregate concentration-normalised profiles per transect in Figure 3 to demonstrate transect-scale linearity and the degree of between-profile consistency. Showing individual profile linear models made the figure difficult to interpret and cumbersome, with little added benefit to the reader. We have clarified this in the caption and text.

Revised manuscript text (Figure 3 caption)

Linear model fit through depth normalised CO2 (a to e) and CH4 (f to j) concentration profiles across TVC transects. Profiles are aggregated per transect to illustrate consistency of profile shape; individual microsite gradients were fitted separately and used for all flux calculations. All gradients are significant with p-values < 0.01 (T test).

Fig. 4: why convert to per day when the measurements are more instantaneous and day is not a SI unit?

Response

We expressed fluxes in mg C m^{-2} day^{-1} for comparability with the recent winter-flux literature, in which day^{-1} is the prevailing convention (Natali et al., 2019; Mavrovic et al., 2023; Voigt et al., 2023; Mavrovic et al., 2025). We have added SI-equivalent values in Results.

Revised manuscript text (Results)

Methane fluxes have less distinct relationship with soil surface temperature than CO2 fluxes. T1-Shrub, T2-Mixed and T3-Tussock microsites were all below -6 °C and showed very little CH4 emissions, with two high emitting microsites (up to 0.58 mgC m-2 d^{-1} or 0.56 nmol m^{-2} s^{-1}) in the coldest transect T3. All fluxes measured in T4-Forest and had basal temperatures were above -5 °C and showed weak net CH4 sinks between 0 and -0.1 mgC m-2 day-1 (-0.10 nmol m-2 s-1).

Fig. 7 makes some interesting methodological points. Fig. 8 as well but what is the mathematical significance of the 19.4%? For comparison with Mavrovic?

Response

The referee understood correctly. The 19.4 % is the relative uncertainty attributed to the CO_2 concentration-gradient ($d[CO_2]/dz$) linear regression in the error budget of Mavrovic et al. (2023) for manually sampled snowpack fluxes at the same site. We adopted it as an external, method-based tolerance for judging whether a subsample median (Md_n) is different to the the full-sample median (Md_{full}). It is not a statistical significance level but a precision band matched to the accuracy achievable by the gradient method, chosen so that the subsampling comparison is directly interpretable against Mavrovic et al. (2023). We have expanded the statement describing this choice in Methods.

Revised manuscript text (Methods)

Subsampled Md_n were considered different to the median of total number of flux measurements from each transect (Md_{full}) when the ratio Md_n / Md_{full} fell within the 19.4 % relative uncertainty reported for the CO_2 concentration-gradient (d[CO2]/dz) regression of manually sampled snowpack fluxes at Trail Valley Creek by Mavrovic et al. (2023). This tolerance is a method-based precision band rather than a statistical significance level, adopted so that the subsampling result is directly comparable with the accuracy achievable by the gradient method.

419: this is in part due to advection of gas in the snowpack

Response

The passage attributed profile homogenisation and non-linearity in basal layers solely to diffusive homogenisation in depth hoar. The referee's observation connects directly to the broader concern raised in the major methological comment. We addressed this observation in detail in within our response to the referee's major comment, and within revisions to the manuscript Methods (Sections 2.1 and 2.3) and Discussion (Sections 4.2 and 4.3).

Fig. A1: really cool sites!

Response

We thank the referee, and we agree!

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