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:

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

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?

<u>Response</u>

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}, $D_{0,\mathrm{CO2}}$, $D_{0,\mathrm{CH4}}$) throughout the equations and text.

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

<u>Response</u>

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

<u>Response</u>

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 $D_{0,\mathrm{CO2}} = 0.1381\ \mathrm{cm^2\ s^{-1}}$ ($1.381 \times 10^{-5}\ \mathrm{m^2\ s^{-1}}$) and $D_{0,\mathrm{CH4}} = 0.1952\ \mathrm{cm^2\ s^{-1}}$ ($1.952 \times 10^{-5}\ \mathrm{m^2\ s^{-1}}$) 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?

<u>Response</u>

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

<u>Response</u>

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?

<u>Response</u>

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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