# *Supplementary Information:* Simulating net ecosystem exchange under seasonal snow cover at an Arctic tundra site

*Correspondence to*: Victoria Dutch (victoria.dutch@polarnetwork.org; Modelling), Oliver Sonnentag (oliver.sonnentag@umontreal.ca; eddy covariance data PI), and Gabriel Hould Gosselin (ghouldgosselin@wlu.ca; eddy covariance infrastructure maintenance and data processing).

## 1.0: Eddy covariance processing

### 1.1: Data processing protocol

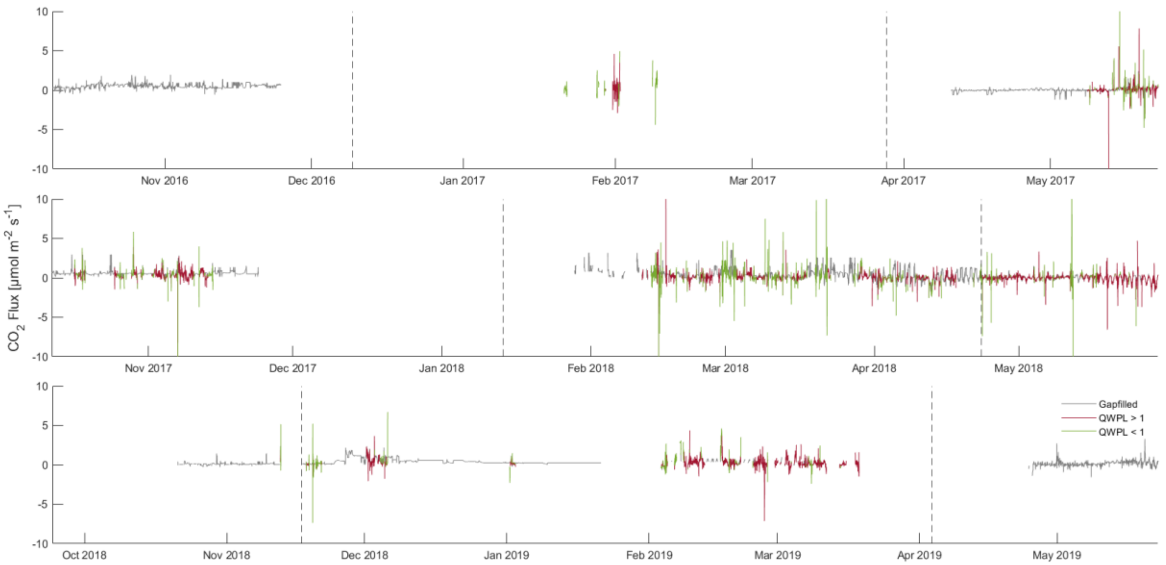
Fluxes used to evaluate simulations were derived from eddy covariance (EC) data collected at TVC. Fluctuations in $CO_2$ concentrations and water vapour densities, and vertical wind velocities and sonic temperatures were measured using an EC150 open-path infra-red gas analyser and CSAT3A sonic anemometer respectively (both Campbell Scientific, Logan, Utah) at a height of 4.08m. Sensor separation between the EC150 and CSAT was -3.2cm northward separation and -2.4cm eastward separation, with the CSAT orientated at 308° relative to true North.  High frequency data was measured at a frequency of 10 Hz and recorded using a CR3000 datalogger (Campbell Scientific). Instruments were recalibrated twice annually; shortly before snow melt commenced and towards the end of the growing season (approximately late March and August/September respectively).

Processing of eddy covariance data followed the procedure outlined in Helbig et al. (2017). Half hourly fluxes were calculated using EddyPro software (Version 6.0 +;  Li-COR Biosciences, Lincoln, Nebraska). A double rotation was used for sonic anemometer tilt correction, spikes in the high frequency timeseries were removed as per Vickers and Mahrt (1997), and sonic temperatures were corrected for humidity effects as per Van Dijk et al. (2004). Block averaging was used to create the half-hourly timeseries, and a covariance maximization procedure detected time lags. Corrections were then applied, as described in Section 1.1.1. A minimum friction velocity value of 0.1 m $s^{-1}$ was used for filtering data. This is a reasonably conservative value, and due to the low-lying nature of the vegetation at TVC a smaller value could be used in the future, increasing data availability. After filtering, data were then gap-filled as outlined in Section 1.1.2. For timeseries plots, mean daily values were calculated from the gap-filled half hourly fluxes and converted to g C $m^{-2}$ $day^{-1}$. Fluxes were then converted to mean weekly values. Data in Section 1 are shown in native measurement units (μmol $CO_2$ $m^{-2}$ $s^{-1}$) as the unit conversation occurred at the end of the data processing protocol.

Uncertainties for the corrected half-hourly fluxes were derived as per Lasslop et al. (2008). This method accounts for random errors using the same autocorrelation principles used to gap-fill the dataset, with the standard deviation of residuals from the gap-filling algorithm used to determine the error.

### 1.1.1: Flux corrections

The Webb-Pearman-Luening (WPL) correction is required to correct measurements of fluxes of trace gases in open-path gas analysers for changes in the density and temperature of air in the path of the analyser. WPL corrections are often of a similar magnitude to calculated fluxes, adding uncertainty to the derived fluxes. The impact of WPL corrections are magnified in Arctic environments, with WPL corrections orders of magnitude larger than calculated fluxes. In order to assess the contribution of this correction to the calculated flux values, we calculate the WPL quality flag (QWPL), as described by Jentzsch et al. (2021). This flag is strongly influenced by very small flux values; QWPL values tend towards infinity as the measured flux approaches zero and small flux changes can lead to large changes in the QWPL flag. Jenztch et al. (2021) advise caution for QWPL values over 1. This occurs when the magnitude of the WPL correction is greater than the magnitude of the final, corrected flux. The proportion of this potentially lower quality data is presented in Supp. Table 1 & Supp. Fig. 1; however, we do not treat data with different quality flags differently when evaluating simulations.




**Supplementary Figure 1: Quality and availability of reference eddy covariance data for all 3 winters. Dashed vertical lines represent freeze-up, midwinter, and thaw periods, as used for model evaluation (Figure 4).**

Large values of WPL corrections, and subsequently QWPL flags, are likely to occur under stable atmospheric conditions, accompanied by large fluxes of sensible heat. Additionally, multiple terms in the WPL correction equation are temperature-dependent, with values up to 15% larger derived for temperatures of approximately -30 ℃ than at 0 ℃ (Jentzsch et al., 2021). Subsequent to WPL corrections, spectral corrections, after Moncrieff et al. (1997); (2004), were applied to the calculated $CO_2$ flux values prior to gap-filling.

**1.1.2: Gap-filling**

Data were gap-filled as per Reichstein et al. (2005). The covariation of flux magnitudes with meteorological conditions were used to assign values to missing datapoints, as outlined in Figure A1 of Reichstein et al. (2005). Gap-filled data were assigned one of three quality flags, depending on availability of meteorological observations and measured fluxes under similar meteorological conditions (defined as observed air temperature within ± 2.5 °C, vapour pressure deficit within ± 5.0 hPa and radiation within ± 50 $Wm^2$ of observed values when flux data were available). Data were unable to be gap-filled when no NEE values were available within a window of 140 days either side of the data point, or when no radiation, air temperature or vapour pressure deficit data were available. Such conditions were common when power outages occurred.

| | **% QWPL \|< 1\|** | **% QWPL \|> 1\|** | **% Gapfilled** | **% Available** |
|---|---|---|---|---|
| **2016 – 17** | 6.3<br>(52.9) | 5.6<br>(47.1) | 24.0 | **35.9** |
| **2017 – 18** | 17.8<br>(43.2) | 23.4<br>(56.8) | 24.6 | **65.7** |
| **2018 – 19** | 5.5<br>(36.1) | 9.7<br>(63.9) | 41.8 | **56.7** |

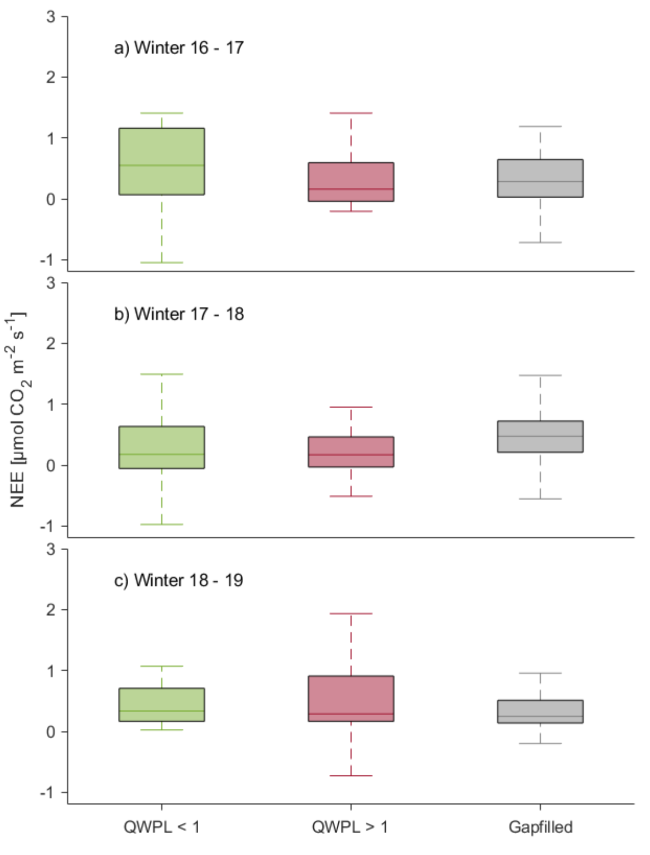
**Supplementary Table 1: Summary of the quality and availability of eddy covariance data for all 3 winters. The proportion of available and non-gapfilled measurements for either quality flag is given in brackets.**

Supplementary Table 1 shows that the proportion of available data is low, particularly in 2018-19, with a high (> 30%) amount of gap-filling needed for model evaluation. However, of data that are available, at least a third and usually closer to half of available data has a QWPL flag indicative of highest quality (QWPL < 1).

**1.2: Limitations**

Measurements of $CO_2$ concentrations between December and February were highly intermittent. Data loss due to power issues was common; many challenges impact maintenance of a constant power supply at a remote Arctic field site during periods of 24-hour darkness and extreme cold. Icing of the instruments (where the optical path of sensors becomes obstructed by rime or precipitation), temperatures below the specification of the instrument, and stable atmospheric conditions impact data coverage and further contribute to data uncertainty. Atmospheric stability also leads to changes in the footprint of the EC tower (Burba and Anderson, 2005), increasing uncertainty about the area being measured and thus the magnitude per $m^2$ of the derived fluxes. Additionally, Pirk et al. (2017) suggest that fluxes derived from the eddy covariance method during snowmelt may be subject to sizable biases due to increased surface heterogeneity, e.g.  patchy snow cover, and subsequent variable surface roughness lengths in the tower footprint.

To compare the impact of post-processing and data quality flagging procedures on calculated fluxes, data were grouped by the magnitude of the WPL correction (green or red in Supp. Fig. 2) and if it was derived by the gap-filling process (grey in Supp. Figs 1 & 2). Fluxes within these different groups were of similar magnitudes, with no group having a significantly different mean value in all 3 years (analysis of variance gives $F_{16\text{-}17} = 2.32$, $F_{17\text{-}18} = 0.69$ and $F_{18\text{-}19} = 1.71$, none of which are significant at the 0.01 level), suggesting that the inclusion of data with a QWPL flag >1 does not unduly influence the analysis.

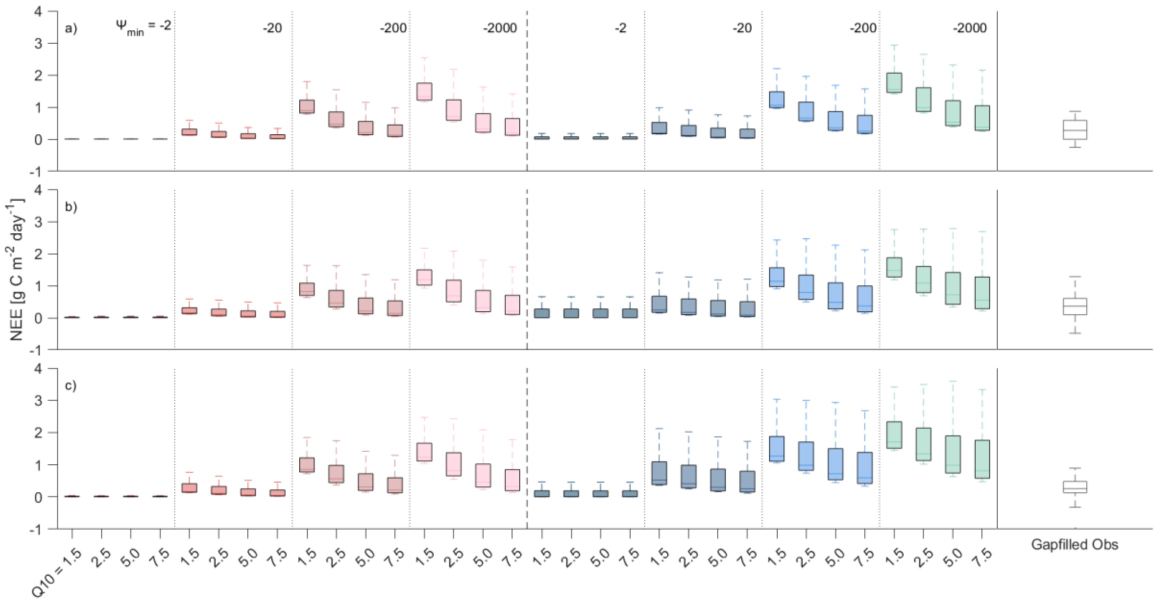



**Supplementary Figure 2: Magnitude of the measured NEE from the Eddy Covariance tower for all 3 winters for each of the different quality flags; High (red) and low (green) values of the QWPL flag, and fluxes produced by the gap-filling algorithm (grey).**

## 2.0: CLM5.0 Simulations

### 2.1: Sensitivity test results

Simulated net ecosystem exchange for the snow-covered non-growing season was evaluated in a sensitivity study using a 32-member ensemble of CLM5.0. This sensitivity test examined the parameterisation of snow thermal conductivity, and how the simulated soil respiration was related to both soil moisture ($\Psi_{min}$) and temperature (Q10).




**Supplementary Figure 3: Net Ecosystem Exchange from the snow-covered non-growing season of each winter of the study for each of the model runs (hourly) and the eddy covariance tower observations (half-hourly) for the winters of a) 2016 – 17, b) 2017 – 18 and c) 2018 - 19. Red tones represent simulations using the Jordan (1991) parameterisation of snow thermal conductivity, and blue tones represent simulations using Sturm et al. (1997). Darker colours (towards the left) represent less negative values of $\Psi_{min}$ and paler colours (towards the right) represent more negative values of $\Psi_{min}$.**

**References**

Burba, G. and Anderson, D.: A Brief Practical Guide to Eddy Covariance Flux Measurements: Principles and Workflow Examples for Scientific and Industrial Applications, 2005.

Helbig, M., Chasmer, L. E., Kljun, N., Quinton, W. L., Treat, C. C., and Sonnentag, O.: The positive net radiative greenhouse gas forcing of increasing methane emissions from a thawing boreal forest-wetland landscape, Glob Chang Biol, 23, 2413-2427, 10.1111/gcb.13520, 2017.

Jentzsch, K., Boike, J., and Foken, T.: Importance of the WPL correction for the measurement of small CO2 fluxes, Atmospheric Measurement Techniques, 14, 7291-7296, 10.5194/amt-14-7291-2021, 2021.

Jordan, R.: A One-Dimensional Temperature Model for a Snow Cover - Technical Documentation for SNTHERM.89, 1991.

Lasslop, G., Reichstein, M., Kattge, J., and Papale, D.: Influences of observation errors in eddy flux data on inverse model parameter estimation, Biogeosciences, 5, 1311-1324, 10.5194/bg-5-1311-2008, 2008.

Moncrieff, J., Clement, R., Finnigan, J., and Meyers, T.: Averaging, detrending, and filtering of eddy covariance time series, in: Handbook of Micrometerology, edited by: Lee, X., Massman, W., and B, L., 7-31, 2004.

Moncrieff, J., Massheder, J., de Bruin, H., Elbers, J., Friborg, T., Heusinkveld, B., Kabat, P., Scott, S., Soegaard, H., and Verhoef, A.: A system to measure surface fluxes of momentum, sensible heat, water vapour and carbon dioxide, Journal of Hydrology, 188-189, 589-611, 1997.

Pirk, N., Sievers, J., Mertes, J., Parmentier, F.-J. W., Mastepanov, M., and Christensen, T. R.: Spatial variability of CO2 uptake in polygonal tundra: assessing low-frequency disturbances in eddy covariance flux estimates, Biogeosciences, 14, 3157–3169, 10.5194/bg-14-3157-2017, 2017.

Reichstein, M., Falge, E., Baldocchi, D., Papale, D., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Gilmanov, T., Granier, A., Grunwald, T., Havrankova, K., Ilvesniemi, H., Janous, D., Knohl, A., Laurila, T., Lohila, A., Loustau, D., Matteucci, G., Meyers, T., Miglietta, F., Ourcival, J.-M., Pumpanen, J., Rambal, S., Rotenberg, E., Sanz, M., Tenhunen, J., Seufert, G., Vaccari, F., Vesala, T., Yakir, D., and Valentini, R.: On the separation of net ecosystem exchange into assimilation and ecosystem respiration: review and improved algorithm, Global Change Biology, 11, 1424-1439, 10.1111/j.1365-2486.2005.001002.x, 2005.

Sturm, M., Holmgren, J., Konig, M., and Morris, K.: The thermal conductivity of seasonal snow, Journal of Glaciology, 43, 26-41, 10.3189/s0022143000002781, 1997.

van Dijk, A., Moene, A. F., and de Bruin, H. A. R.: The principles of surface flux physics: Theory, practice and description of the ECPACK library, Wageningen University, Wageningen, The Netherlands, 2004.

Vickers, D. and Mahrt, L.: Quality Control and Flux Sampling Problems for Tower and Aircraft Data, Journal of Atmospheric and Oceanic Technology, 14, 512-526, 10.1175/1520-0426(1997)014<0512:Qcafsp>2.0.Co;2, 1997.