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Simulating net ecosystem exchange under seasonal snow cover at an Arctic tundra site

Victoria R. Dutch et al.

Correspondence to: Victoria R. Dutch (v.dutch@uea.ac.uk) and Oliver Sonnentag (oliver.sonnentag@umontreal.ca)

S1.0: Eddy covariance processing

S1.1: 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. As different instruments on the EC tower are at different heights (see Section 2.1), but CLM5.0 only allows the use of one forcing height, we carry out all our simulations using a forcing height (ZBOT) of 2 m. No scaling of measurements was undertaken to the 2 m simulated forcing height. Sensor separation between the EC150 and CSAT was -3.2 cm northward separation and -2.4 cm 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 S1.1.1. A minimum friction velocity value of 0.1 m s^{-1} was used for filtering data. This is 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 S1.1.2. 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 of this supplement 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.

S1.1.1: 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 Table S1 & Fig. S1; however, we do not treat data with different quality flags differently when evaluating simulations.

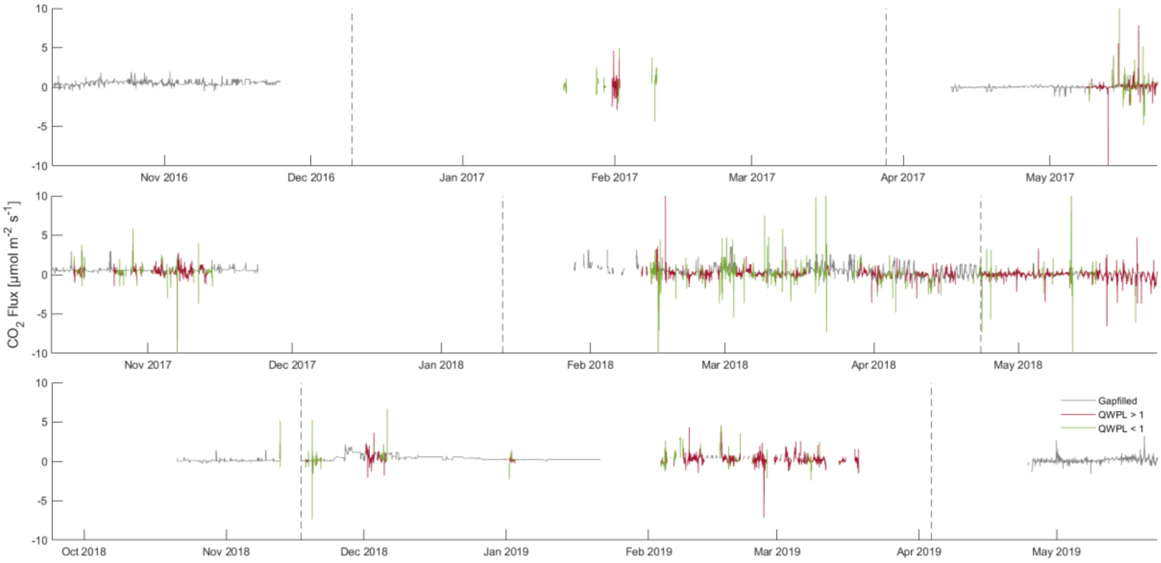

Figure S1: Quality and availability of reference eddy covariance data for all 3 winters. Dashed vertical lines represent freeze-up, midwinter, and thaw periods, as used for model evaluation (Figure 4).

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°C than at 0°C (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.

S1.1.2: 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 ± 50Wm^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 (52.9)	5.6 (47.1)	24.0	**35.9**
2017 – 18	17.8	23.4	24.6	**65.7**

	(43.2)	(56.8)		
2018 – 19	5.5 (36.1)	9.7 (63.9)	41.8	**56.7**

Table S1: 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.

Table S1 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).

S1.2: 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 Figs S1 & S2) and if it was derived by the gap-filling process (grey in Figs S1 & S2). 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.

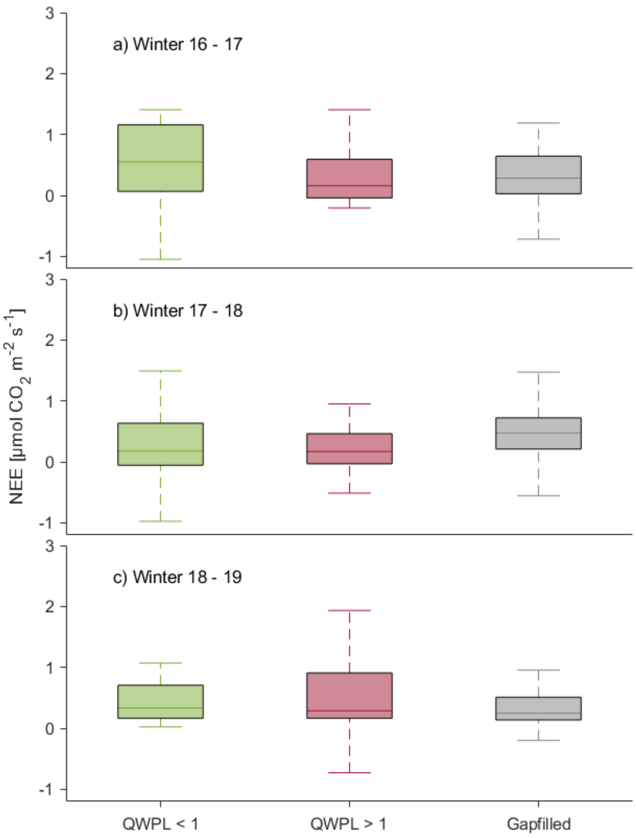

Figure S2: Magnitude of the measured NEE from the Eddy Covariance tower for all 3 winters for each of the different quality flags; High (red) and low (green) values of the QWPL flag, and fluxes produced by the gap-filling algorithm (grey).

S2.0: CLM5.0 Simulations

S2.1: 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 (Ψ_{min}) and temperature (Q10).

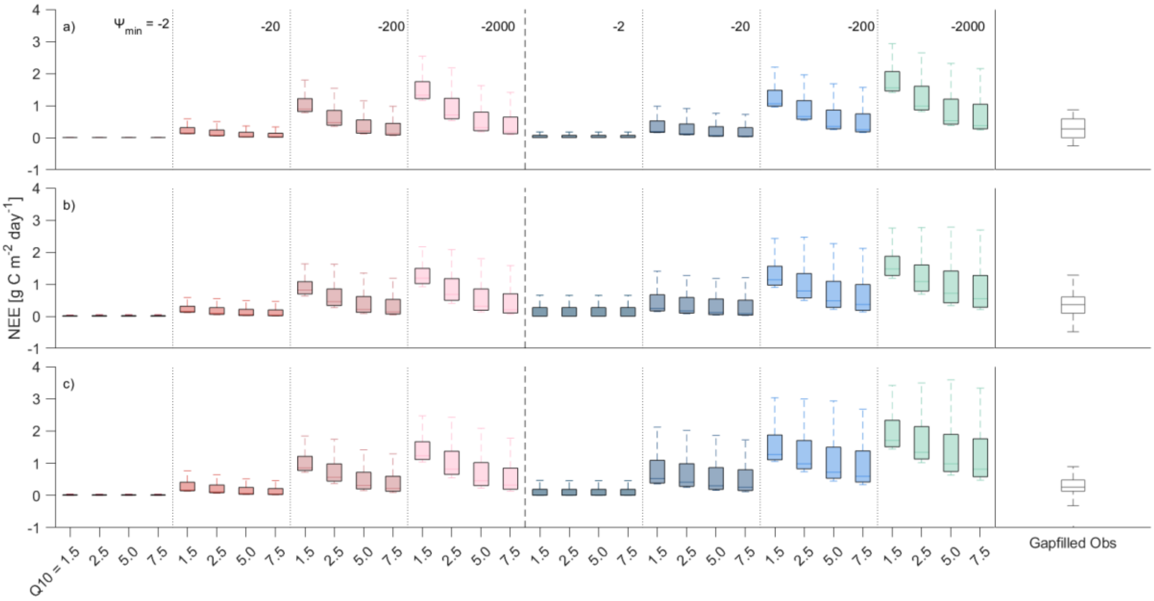

Figure S3: Net Ecosystem Exchange from the snow-covered non-growing season of each winter of the study for each of the model runs (hourly) and the eddy covariance tower observations (half-hourly) for the winters of a) 2016 – 17, b) 2017 – 18 and c) 2018 - 19. Red tones represent simulations using the 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 Ψ_{min} and paler colours (towards the right) represent more negative values of Ψ_{min}.

S2.2: Impact of Soil Texture and Carbon Content on Simulated Respiration

Additional simulations to test the impact of soil texture and carbon content on simulated respriation were carried out and are discussed in Section 3.3. We tested 3 different profiles of soil organic matter content; SOM1 is the CLM default (used in all simulations outside of this section of the paper), SOM2 is the values used by default in Cryogrid, and SOM3 uses observed SOM values from Boike et al [Unpublished] interpolated onto CLM soil layers. We also tested 2 different soil texture profiles; SC1 is the CLM default and SC2 uses observations interpolated onto CLM soil layers. The values used for these different soil profiles are given in Table S2 below, and the resultant simulated soil respiration is given in Fig. S4.

Soil layer	Upper interface (m)	Lower interface (m)	SOM1	SOM2	SOM3	SC1		SC2	
			Organic Matter Content (kg m^{-3})			% Sand	% Clay	% Sand	% Clay
1	0	0.02	130	77.9	33.5	28	36	14	17
2	0.02	0.06	88.7	65.7	33.5	28	36	14	17
3	0.06	0.12	56.5	64.8	33.5	28	36	20	19
4	0.12	0.20	35.4	63.3	33.5	28	36	25	12
5	0.20	0.32	22.1	55.3	22.1	28	36	25	16
6	0.32	0.48	13.8	46.6	13.8	28	36	25	16
7	0.48	0.68	8.6	39.0	8.6	28	36	25	16
8	0.68	0.92	5.4	29.9	5.4	28	36	25	16
9	0.92	1.20	0	0	0	28	36	25	16
10	1.20	1.52	0	0	0	28	36	25	16

Table S2: Soil properties used in additional simulations discussed in Section 3.3.

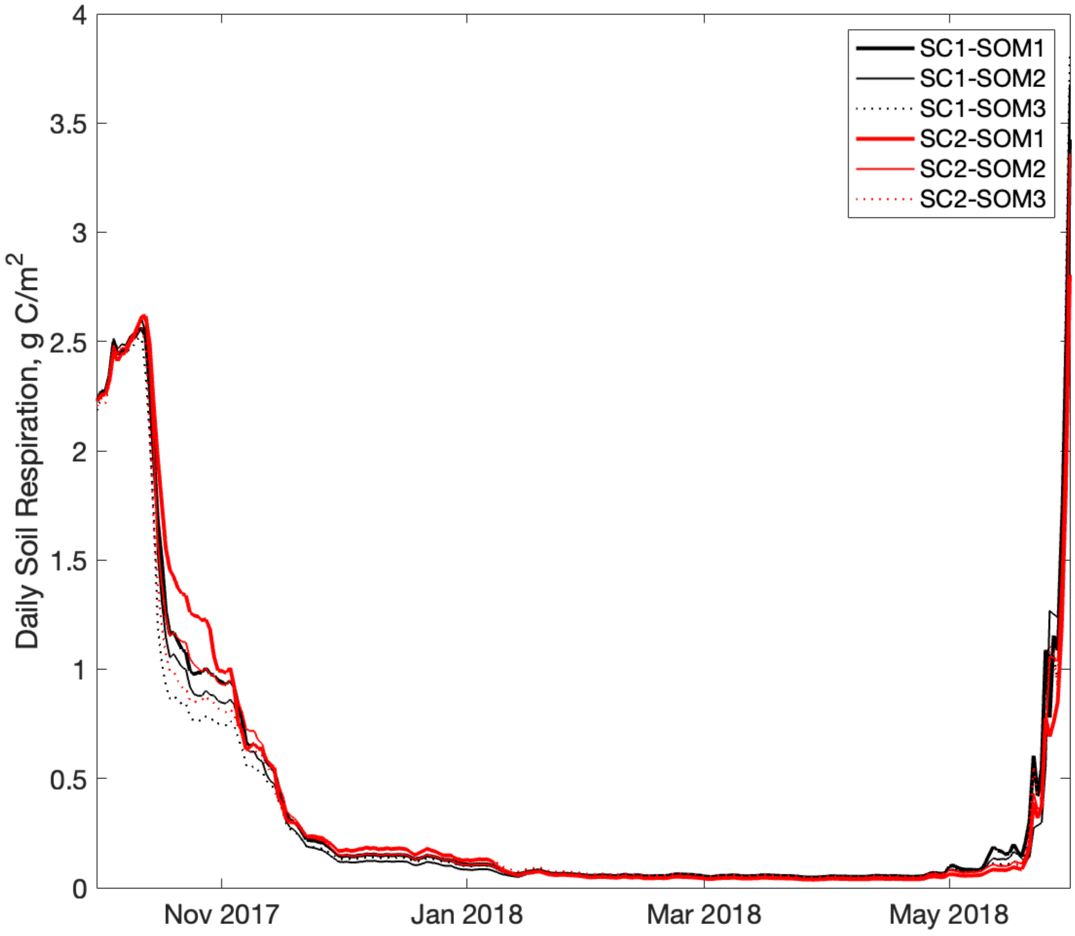

Figure S4: Simulated soil respiration for each combination of soil profiles shown in Table S2. The two colours (black and red) denote different soil texture profiles, and the three line styles (thick, thin and dotted) denote the three different soil organic matter profiles.

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