High-quality eddy-covariance CO₂ budgets under cold climate conditions

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Key Points:
- Self-heating of the open-path gas analyzer can lead to systematic offsets in CO₂ flux budgets, causing an annual bias of about 100 gC m⁻²
- Sonic anemometer heating directly affected temperature measurements but not the turbulent wind field
- Both instrument heating effects have to be considered to compute unbiased CO₂ budgets in cold ecosystems

Abstract

This study aimed at quantifying potential negative effects of instrument heating to improve eddy covariance flux data quality in cold environments. Our overarching objective was to minimize heating-related bias in annual CO₂ budgets from an Arctic permafrost system. We used continuous eddy-covariance measurements covering three full years within an Arctic permafrost ecosystem with parallel sonic anemometers operation with activated heating and without heating as well as parallel operation of open- and closed-path gas analyzers, the latter serving as a reference.

Our results demonstrate that the sonic anemometer heating has a direct effect on temperature measurements while the turbulent wind field is not affected. As a consequence, fluxes of sensible heat are increased by an average 5 W m⁻² with activated heating, while no direct effect on other scalar fluxes was observed. However, the biased measurements in sensible heat fluxes can have an indirect effect on the CO₂ fluxes in case they are used as input for a density-flux WPL correction of an open-path gas analyzer.

Evaluating the self-heating effect of the open-path gas analyzer by comparing CO₂ flux measurements between open- and closed-path gas analyzers we found systematically higher CO₂ uptake recorded with the open-path sensor, leading to a cumulative annual offset of 96 gC m⁻², which was not only the result of the cold winter season but also due to substantial
self-heating effects during summer. With an inclined sensor mounting, only a fraction of the self-heating correction for vertically mounted instruments is required.

1. Introduction

Vast permafrost carbon pools threatened by amplified climate change effects make the Arctic a key region in the context of global climate change. Still, to date only very limited information is available regarding cold season carbon cycle processes in Arctic permafrost ecosystems, mostly caused by highly challenging logistics and harsh environmental conditions. With the option to record continuous flux time series that are representative at the ecosystem scale [Aubinet et al., 2012], the network of eddy-covariance (EC) sites has grown considerably over the past decades, including coverage of complex terrain that is difficult to access with other monitoring techniques [Eugster and Merbold, 2015; Foken, 2017; Monson and Baldocchi, 2014; Wyngaard, 2010]. For Arctic environments, however, data coverage is still comparatively sparse [Oechel et al., 2014], largely linked to the challenges with respect to installation and selection of suitable instrumentation, power supply, and maintenance capacity. In addition, Arctic flux measurements may be negatively affected by heating effects of the instrumentation, particularly during Arctic winter conditions [Goodrich et al., 2016], causing e.g. systematic biases in observed annual carbon budgets. Here we investigate these heating effects at a site in northeastern Siberia and develop suggestions how to minimize such biases.

The limitations of Arctic EC data coverage become particularly aggravated when it comes to flux observations beyond the growing season, since observations over the long winter season are still extremely rare. Consequently, in the past annual balances of Arctic EC fluxes were often estimated with crude approximations regarding wintertime fluxes, i.e. zero exchange from frozen soils was assumed. This approach has been shown to lead to systematic biases of the annual net CO2 budgets in Arctic regions [Euskirchen et al., 2012; Lüers et al., 2014; Marushchak et al., 2013; Oechel et al., 2014; Zimov et al., 1996]. Non-zero wintertime CO2 fluxes can e.g. be linked to plant and microbial respiration of cold-tolerant species [Bate and Smith, 1983; Coyne and Kelley, 1974; Kappen, 1993; Kelley et al., 1968; Panikov et al., 2006], CO2 loss during freeze-thaw dynamics [Grogan et al., 2004; Pries et al., 2013], free soil water creating warm microenvironments in frozen soils [Zimov et al., 1993] and unfrozen patches during the re-freezing in the fall [Mastepanov et al., 2008; Zona et al., 2016]. Consequently, the continuous coverage of cold season CO2 fluxes is critically important to assess the role of Arctic ecosystems within the context of global climate change.

As part of an EC system to monitor the CO2 exchange, depending on the site characteristics and research purpose, open-path (OP) or closed-path (CP) gas analyzers can be used. Both options feature different advantages and disadvantages in their application [Munger et al., 2012]. Open-path configurations provide in-situ measurements, while having a comparably low power and maintenance demand and are therefore widely used to determine CO2 fluxes between the surface and the atmosphere [Haslwanter et al., 2009], especially in the Arctic. However, the operation of an open-path gas analyzer (LI-7500) may lead to systematic biases of CO2 fluxes towards implausible uptake [Amiro, 2010; Clement et al., 2009; Helbig et al., 2016; Oechel et al., 2014; Ono et al., 2007] that can be linked to instrument heating. Heat is artificially generated by the instrument electronics housed below the optical path and results in higher temperatures within the optical path, generating an additional sensible heat flux inside the open optical measurement path. This effect has implications on the determined covariance, since this process is not accounted for by the traditional Webb-Pearman-Leuning (WPL) density-flux correction [Webb et al., 1980]. In an attempt to develop a direct instrumental solution for this problem, Grelle and Burba [2007] and Massman and Frank [2009] added fine-wire thermometers within the optical path of the LI-7500 to account for the
influence of high frequency temperature fluctuations. As a simplified alternative, a correction procedure to amend the performance of the instrument without the need for additional sensor installations was developed [Burba et al., 2006; 2008]. However, while the use of the self-heating correction has increased [Reverter et al., 2011], the application can vary depending on the instrumental setup [Burba and Anderson, 2010b]. The self-heating correction allows offsetting the flux biases induced by instrument self-heating [Burba et al., 2008; Reverter et al., 2011]. Alternatively, site-specific corrections can be determined using parallel CP measurements as a reference [Järvi et al., 2009]. If no parallel measurements are available, a generic scaling factor can be used [Rogiers et al., 2008]. Still, the self-heating correction for OP sensors is subject to large uncertainties, and it has been shown that its correct application needs to be customized for individual cases [Bowling et al., 2010; Haslwanter et al., 2009; Wohlfahrt et al., 2008]. Consequently, there is no general consensus on the application of the self-heating correction. Since the concept behind the correction assumes strongest heating effects under cold ambient air conditions [Burba et al., 2006; 2008], the correction is usually applied only for cold ecosystems.

Another important technical aspect for the operation of EC systems under cold Arctic conditions is the application of a heating device to avoid rime and/or icing at the transducers of the sonic anemometer. During periods with high air humidity in combination with temperatures close to freezing, ice crystals can build up around the transducers of the sonic anemometer and disturb measurements [Makkonen and Laakso, 2005]. Heating systems to avoid ice buildup can be implemented as built-in versions by the manufacturer. Alternatively, customized versions can be installed using, e.g., heating tape or resistive heating wires wrapped around transducers [Goodrich et al., 2016; Skelly et al., 2002]. A suitable scheme to activate the heating device should be applied to ensure good instrument conditions and counteract icing events, but at the same time to minimize heating periods to avoid biasing the measurements. Increased sensible heat fluxes [Skelly et al., 2002] and resulting overestimations in carbon dioxide and latent heat fluxes [Goodrich et al., 2016] have been linked to active instrument heating. This calls for heating schemes that are based on meteorological conditions, triggering an activation, e.g., at high humidity and temperatures around freezing, instead of a continuous heating regardless of prevailing environmental conditions.

In summary there are several issues related to quantifying the turbulent CO$_2$ fluxes between the surface and the atmosphere and the estimation of reliable winter budgets in Arctic ecosystems. So far, no general recommendation to minimize associated data gaps, and particularly to avoid biases related to instrument heating, was developed. In this study we assess the quantitative effect of different instrument heating options: 1) the self-heating of the OP gas analyzer and 2) the heating of the sonic anemometer that was activated based on meteorological conditions. Measured scalars from both instruments, the vertical wind component from the sonic anemometer and the CO$_2$ concentration from the OP system are essential to determine the turbulent CO$_2$ flux. Our findings build on continuous EC measurements from a field site near Chersky in northeastern Siberia covering three complete winter seasons. This dataset covers parallel operation of heated and unheated sonic anemometers as well as parallel operation of OP and CP gas analyzer systems. This setup allows for a comprehensive assessment of the effect of different instrument heating options on continuous EC CO$_2$ flux measurements during Arctic winter and will be used to derive recommendations on how to minimize the bias in cases where only OP measurements are available. Therefore both heating effects are analyzed separately and the effect of each heating system on the determined CO$_2$ exchange fluxes is evaluated. Different formulations on the self-heating effect (1) are introduced in section 2.3, corresponding results are presented in section 3.1 and these results are discussed in section 4.1. For analysis of an active sonic
anemometer heating effect (2) the heating scheme is presented in section 2.4 results are described in section 3.2 and discussed in 4.2.

2. Material and methods

2.1. Instrumentation setup

Measurements were carried out at a field site (68.75°N, 161.33°E) close to the city of Chersky in the northeastern part of Siberia, Russia. The study site was characterized as moist tussock tundra with a mean elevation of 6 m a.s.l. and an average snow depth of 0.6 to 1 m during winter. Two towers with an identical instrumentation were installed within a distance of about 600 m to monitor exchange fluxes between the surface and atmosphere. One tower is placed within a circular drainage ditch system and the second tower reflects undisturbed conditions. While the analysis on the drainage disturbance focuses on the summer season, uniform conditions at both towers with frozen soil and a closed snow cover are assumed in the winter.

The EC instrumentation was mounted on top of each tower at a height of 4.9 m and 5.1 m for tower 1 and 2, respectively, including a heated sonic anemometer (uSonic-3 Scientific, former USA-1, METEK GmbH, Elmshorn, Germany; with integrated 55 W heating) and two types of gas analyzers (GA). The open-path GA (inclined by 15° towards ESE, LI-7500, LI-COR Biosciences Inc., NE, USA) was installed in summer 2013, while the closed-path GA (FGGA, Los Gatos Research Inc., CA, USA.) was added in spring 2014. The CP systems consist of an inlet placed next to the sonic anemometer (vertical sensor separation: 0.30 m), a sampling line (heated and insulated Eaton Synflex® (former name decabon) with 6.2 mm inner diameter and a length of 16.0 m and 12.8 m for Tower 1 and 2, respectively), and an external vacuum pump (KNF N940 membrane pump, flow rate of 13 L min⁻¹ at ambient pressure).

Data collection was running continuously at both towers since the installation mid-summer 2013 until spring 2016. Both GAs were running in parallel on tower 1 from spring 2014 until spring 2016, while on tower 2 the OP sensor was operational from July 2013 to July 2014, while afterwards only the CP measurements were continued. For tower 2 the data collection was stopped in November 2015 due to a malfunction of the CP GA. While growing season measurements were reported by Kittler et al. [2016], the focus of the this study is on winter-season, here defined as the period from 1st of November to 31st March.

Ancillary measurements of barometric pressure (Pressure Transmitter, 61302V, R.M. Young Company, Traverse City, USA), four radiation components (CNR4, Kipp & Zonen, Delft, The Netherlands) as well as air temperature ($T_a$) and relative humidity ($rH$) combined (KPK 1/6-ME-H38, Mela, Bondorf, Germany, ventilated hut) were collected from the top of the towers and stored on a data logger (CR3000, Campbell Sci. Inc., Logan, USA).

2.2. Data processing

Meteorological data were collected at 10 second intervals and stored on the data logger (CR3000, Campbell Scientific) as 10 minute averages. Data post-processing for these data follows a quality control scheme described in detail by Kittler et al. [2016]. Remaining high quality data were subsequently averaged to 30-minute intervals.

For the EC systems, data were collected at 20 Hz with analogue output for the GAs. Data acquisition on site used the software package EDDYMEAS [Kolle and Rebmann, 2007] on a local computer at the field site. Flux processing was handled with the TK3 software tool [Mauder and Foken, 2015], which implemented all required processing steps and correction procedures. For both, OP and CP GAs, the 2D rotation of the wind field, the cross-wind correction [Liu et al., 2001], and a correction for loss in the high frequency range [Moore, 1986] was applied. For the CP GA the high frequency raw data (as wet mole fraction) were
converted to dry mixing ratios before processing. Since losses in the high-frequency range occur when gases are transferred to the closed-path analyzers through inlet tubes, the flow rate of 13 L min\(^{-1}\) (ambient pressure) translated into a replacement of sample air in the measurement cell at a frequency of \sim 2–2.5 Hz for \(\text{CO}_2\) and \(\text{H}_2\text{O}\), respectively, which were used as cutoff frequencies for the spectral correction of the CP GA. The WPL density-flux correction [Webb et al., 1980] was applied for the OP data to account for density fluctuations within the open optical measurement path.

To ensure high data quality, the standard post-processing quality control scheme based on tests for stationarity and well-developed turbulence [Foken and Wichura, 1996] was extended by additional tests to detect implausible data points in the resulting flux time series. These tests covered a check for absolute limits for \(\text{CO}_2\) flux data (-15 \(\mu\text{mol m}^{-2} \text{s}^{-1}\) < \(\text{CO}_2\) flux < 5 \(\mu\text{mol m}^{-2} \text{s}^{-1}\)), the OP GA status information (gain control maximum < 75), errors messages in the log file reported by the sonic anemometer, a comparison of the absolute concentrations of \(\text{CO}_2\) for the two towers for specific wind directions, a test for \(T_a\) (\(T_a < -40\) ^\circ\text{C}, which is the lowest possible operating \(T_a\) for the sonic anemometer) and a flag for activated sonic anemometer heating. Quality flags (QF) were combined and data with highest quality [QF 1-3, Foken et al., 2005; 2012] were used for the detailed analysis for the self-heating of the OP instrument and the sonic anemometer heating effect (Table 1). For long-term budgets, data covering QF 1-6 [Foken et al., 2005; 2012] were used to increase data coverage for reliable and robust gap filling procedure (Table 1). The gap filling was based on the marginal distribution sampling method [Reichstein et al., 2005], implemented through the R-package “REddyProc” (https://r-forge.r-project.org/projects/reddyproc). For more details on quality tests and gap filling implementation see Kittler et al. [2016]. Statistics on data availability from both towers during the three winter seasons, broken up into data quality categories, are given in Table 1.

Figure 1 lists the timeframes used for studying self-heating effects of the LI-7500 as well as the sonic anemometer heating schemes as described in the following Sections. All statistical analyses were performed with the R software [R Core Team, 2014]. The examination of the wind speed and direction with resulting figures were created with the R-package “openair” [Carslaw, 2015]. Because measurement signals of both the open- and closed-path gas analyzers have approximately the same error [Dunn, 2004], i.e., no one device is free of errors, the orthogonal regression was applied with the R-package “lmodel2” [Legendre, 2014]. Orthogonal regression analysis was used to assess the agreement between OP and CP flux measurements, and Pearson’s correlation coefficients (\(r\)) are given. Orthogonal regression (linear model II regression) is used in place of ordinary least-square regression because it takes experimental uncertainties in both OP and CP measurements into account, and does not require the definition of an independent and a dependent variable.

2.3. Correction for self-heating of the open-path sensor

To account for the self-heating of the OP analyzer a correction was presented by Burba et al. [2008]. Their basic equation used to achieve final \(\text{CO}_2\) fluxes (\(F_c\)), which includes an adjusted version of the original WPL flux-density formulation [Webb et al., 1980], corrects initial \(\text{CO}_2\) fluxes (\(F_0\)) as

\[
F_c = F_0 + \mu \frac{E}{\rho_d} \frac{\rho_c}{1 + \mu \frac{\rho_c}{\rho_d}} + \frac{S}{\rho_c T_a} \rho_c,
\]

on the basis of Eq. (44) of Webb et al. [1980], while commonly Eq. (24) of Webb et al. [1980] is used [Foken et al., 2012; Leuning, 2004; 2007] with a numerical difference less than 1-2 %. The WPL flux-density corrected latent heat flux is given as \(E\) [kg m\(^{-2}\) s\(^{-1}\)], \(\rho_c\) [kg m\(^{-3}\)] as
ambient CO₂ density, ρ [kg m⁻³] as total air mass density, cₚ [J kg⁻¹ K⁻¹] is the specific heat of air, Tₐ [K] as the air temperature, μ is the molar mass ratio of dry air to water vapor given as 1.6077, ρᵥ [kg m⁻³] and ρₐ [kg m⁻³] as partial densities of H₂O and dry air, respectively, and S [W m⁻²] as the sensible heat flux. The resulting unit for the CO₂ flux is kg m⁻² s⁻¹. The sensible heat flux can be determined by different methods depending on the ancillary instrumentation [Burba et al., 2008]. Here, we use “Method 4” from Burba et al. [2008] to estimate the self-heating correction as

\[ S = \rho c_p \frac{w'}{T_a} + S_{Burba} , \]  

(2)

by combining elements from the WPL density-flux correction [Webb et al., 1980] as the first term on the right hand side, while the second term represents the additional sensible heat flux caused by the self-heating of the instrument, here termed S_{Burba}. In Burba et al. [2008] the additional heat flux (here named S_{Burba,2008}) was estimated based on the sensible heat flux from key instrument surfaces of the open-path instrument, namely bottom, top and spar of the sensor as

\[ S_{Burba,2008} = S_{bot} + S_{top} + 0.15 S_{spar}. \]  

(3)

Detailed equations to derive these separate heat fluxes that combine to the S_{Burba,2008} flux are listed in Table 2.

Since the traditional WPL flux-density correction [Webb et al., 1980] is commonly integrated in standardized processing software packages, the focus within this study has been placed on the self-heating term. Accordingly, to separate the self-heating term from the remaining steps, we combined Eqs. (1) and (2) using already WPL density-flux [Webb et al., 1980] corrected CO₂ data (F_CWPL) as

\[ F_c = F_{CWPL} + \xi \frac{S_{Burba} \rho_c}{\rho c_p T_a} , \]  

(4)

The scaling factor \( \xi [-] \) introduced here is not part of the original equation and is explained in the next section. By using a combination of Eq. (4) and Eq. (3) this approach will hereafter be referred to as Burba_2008. A similar approach using F_CWPL as input was proposed by Burba et al. [2006], here again slightly adjusted to achieve consistent units:

\[ F_c = F_{CWPL} + \xi \frac{(T_s - T_a) \rho_c}{r_a T_a} \left( 1 + \frac{\rho_v}{\rho_d} \right). \]  

(5)

\( T_s \) [K] is the instrument surface temperature and \( r_a \) [s m⁻¹] represents aerodynamic resistance. The aerodynamic resistance is determined directly from the friction velocity \( u_* \) [m s⁻¹] and the horizontal wind speed \( u \) [m s⁻¹] as \( r_a = u/(u_*^2) \) according to the simplified bulk approach described in Stull [1988]. Note that we changed the originally used \( q_c \) [\( \mu \)mol m⁻³] for the ambient CO₂ density, which would have yielded CO₂ fluxes in \( \mu \)mol m⁻² s⁻¹, to \( \rho_c \) [kg m⁻³] as used in the preceding equations. This approach is referred to as Burba_2006.

The scaling factor \( \xi \) represents the fraction of the self-induced heat flux relevant for the correction of an inclined LI-7500 sensor. Eq. (5) was used by Rogiers et al. [2008] and further tested by Järvi et al. [2009], both pointing out that for inclined open-path analyzers only a small fraction of this additional heat flux actually influences the measurement path. Accordingly, \( \xi \) can theoretically vary between 0 (no self-heating effect) and 1 (full self-heating effect needs to be applied, e.g. for a vertical sensor orientation). It was demonstrated by Järvi et al. [2009] that only a very small fraction of the full heat flux typically affects measurements that were taken with the recommended sensor inclination angle of 15°.
Putting the self-heating terms of the Burba_2008 and Burba_2006 approaches in relation (for details see SI Eq. (S1) to (S4)) by eliminating duplicate elements, neglecting the term \((1 + \mu p_d/\rho_d)\), since it only increases the heat flux term on the order of 2% and thus is not substantial, and application the formulation for \(r_a\) follows

\[
S_{Burba,2006} = \frac{(T_s - T_a) u^2}{u} \rho c_p. \tag{6}
\]

Eq. (6) as a re-formulation for the additional sensible heat flux emitted by the open-path analyzer with the Burba_2006 approach reveals systematic differences between the approaches. In both cases, a temperature difference between air \((T_a)\) and instrument surface \((T_s)\) is the driving force of the heat flux. The simple Burba_2006 approach uses a bulk surface temperature and parameterized atmospheric resistance to derive heat fluxes. However, in the Burba_2008 approach surface temperatures are estimated for individual parts of the sensor, and converted to individual heat fluxes using formulations proposed by Nobel [1983], and only afterwards combined to a single instrument heat flux.

The instrument surface temperature is a crucial component of the self-heating correction that can be determined directly with additional measurements or can be estimated from \(T_a\) based on various empirical parameterizations (in [K] with \(T_o\) as absolute zero is 273.15). Due to radiative heating over the day and radiative cooling during the night affecting measurements differently with increased effects under non-vertical OP sensor configurations [Burba et al., 2008] some \(T_s\) parameterizations differ between day- and night-time. Night-time conditions were defined by incoming shortwave radiation < 20 W m\(^{-2}\). Consequently, Arctic winter with nearly no solar radiation is mostly represented by night-time conditions, while during summer (June/July) ca. 70 % of each day is characterized as day-time. While for Eq. (4) a set of surface temperature parametrizations for the different instrument parts are given (see Table 2), there is a bulk of parametrizations that can be used in combination with Eq. (5). Based on a polynomial fit from a field experiment:

\[
T_s = 0.0025 \ (T_a - T_o)^2 + 0.9 \ (T_a - T_o) + 2.07 + T_o, \tag{7}
\]

Eq. (7) was found to best reproduce the observed heating effects and increased thermal exchange [Burba et al., 2006]. This equation was determined for the bottom part of the open path sensor, dominating under an inclined sensor mounting and is specified for a temperature range from -25 °C to 20 °C [Burba et al., 2006]. For a forest site, Järvi et al. [2009] developed separate fits for day- and night-time conditions in the temperature range –12 to 28°C

\[
T_{s,\text{day}} = 0.93 \ (T_a - T_o) + 3.17 + T_o \text{ and } T_{s,\text{night}} = 1.05 \ (T_a - T_o) + 1.52 + T_o. \tag{8}
\]

Under the assumption that the true flux was represented by the CP data, \(\xi\) in Eq. (4) and (5) were optimized using a nonlinear least-squares method to achieve optimum agreement between corrected OP and reference CP fluxes. For the optimization, the starting value for \(\xi\) was set to 0.05, as suggested by other studies [Järvi et al., 2009; Rogiers et al., 2008]. The \(\xi\) fraction was optimized separately for both the Burba_2008 and Burba_2006 approach and also separately for the Burba_2006 approach with both \(T_s\) parameterizations.

Since CP data serve as true reference for the optimization, fully corrected CP fluxes are crucial for the application of the correction (e.g., data processing or software). Different factors such as type of instruments, length of inlet tubing, tube diameter and flow rate (see Section 2.1) will systematically affect corrections of CP fluxes [Aubinet et al., 2016; Aubinet et al., 2012; Burba and Anderson, 2010a; Metzger et al., 2016]. For the CP system all applied corrections are seasonally independent and thus the CP system is used as a reference
throughout the year. Furthermore, a correct application of the WPL density-flux correction [Webb et al., 1980] for the OP data is crucial, since otherwise a remaining bias would be projected on the self-heating correction. Here, we applied all recommended correction and used standardized methods for the data processing [Fratini and Mauder, 2014] to ensure highest data quality.

2.4. Sonic anemometer heating and icing events

Using information from ancillary meteorological instrumentation the sonic anemometer heating was controlled by the data logger and was activated (heater switched on) based on combined $rH (> 85 \%)$ and $T_a (< 1 ^\circ C)$ conditions. This heating scheme was designed to avoid icing and riming on the transducers. Documented icing events occurred during deactivated heating periods before, during or after the icing events. Following an icing event, ice was either removed manually by the site technician after the detection or may have disappeared due to sublimation. This can alter the residence time and might cause differences in the icing event length between sonic anemometers, shorten icing events even if conditions would continue to promote icing or lead to icing at individual sensors.

Since the same heating schemes were applied at both towers, and both towers experienced almost identical meteorological conditions, the sonic anemometer heating should be activated synchronously at both towers. Due to a reset of sonic anemometer setup parameters, the sonic anemometer heating was shut down and excluded from the heating activation protocol (hereafter referred to as non-heated) for two periods (tower 2: mid-October 2013- April 2014, tower 1: mid-January - May 2015), while at the other tower the heating was controlled by the data logger and activated based on meteorological conditions (hereafter referred to as controlled-heating). Thus, during these phases conditions between non-heated sonic anemometer and the sonic anemometer with controlled heating can be compared for cases with activated heating (e.g. controlled-heating activated) and without heating at both sonic anemometers. For reasons of data quality assessment, the data analysis of the heating effect for the first period was restricted until the end of 2013 (Figure 1). Heated and unheated conditions are compared during both winter seasons by combining data from both observation systems (e.g. heated conditions represent data from tower 1 during the first winter season and data from tower 2 during the second winter season). It is assumed that during the polar winter with a closed snow cover, variability in microsite conditions between the towers can be neglected. In total 26 weeks are available for an in-depth analysis of the sonic anemometer heating.

For the identification of potential icing events, error messages given by the sonic anemometer were analyzed. Error messages were recorded with a frequency of 20 Hz and stored additionally to the high frequency EC data in an extra file and were counted per half-hour interval for the same temporal resolution as for EC data without distinguishing between individual error messages. These additional data logs indicate potential disturbance or blockings of the sonic anemometer signal. Icing events were identified as periods with the maximum number of error messages per half hour (36000), indicating a “permanent” disturbance of measurements that is unlikely to be caused by short-term meteorological conditions. Since EC data during icing events are inaccurate ancillary measurements are used to characterize meteorological conditions.
3. Results

3.1. Self-heating of open-path sensor

3.1.1. Differences between non-self-heating corrected open-path gas analyzer and closed-path reference data

Wintertime CO₂ fluxes obtained from the OP and CP were correlated ($r = 0.97$, $N > 5700$) showing that both measurement systems generally capture the same signal. With an orthogonal regression analysis ($CP = \text{Intercept} + \text{Slope} \cdot \text{OP}$) an intercept of $-0.284 (-0.294 - 0.274$ as 95% confidence interval) µmol m$^{-2}$ s$^{-1}$ and a slope of $1.142 (1.135 - 1.150$ as 95% confidence interval) were obtained. A negative intercept indicates that the OP has the tendency towards more negative CO₂ fluxes, i.e. more uptake by the ecosystem. Even under cold ambient conditions with completely frozen soils and monthly mean $T_d$ below -30 °C (DJF) where active assimilation of CO₂ by the ecosystem is virtually impossible, average CO₂ fluxes ranged around or below zero with the operation of an OP ($-0.18 \pm 0.71$ µmol m$^{-2}$ s$^{-1}$), while the reference CP shows positive mean CO₂ fluxes ($0.19 \pm 0.4$ µmol m$^{-2}$ s$^{-1}$, see SI Figure S1).

These observations suggest a systematic bias in OP measurements that can only be clearly demonstrated during wintertime, since no other influence factors (e.g. uptake by meteorological or biological forcing) besides instrument self-heating can cause negative flux rates. However, carbon dioxide flux offsets between OP and CP systems show similar tendencies over the full annual cycle (Figure 2 a), resulting in a cumulative offset of 96 gC m$^{-2}$ for the data year 2015. Discrepancies in net flux rates between the OP and the CP were found to have different gradients for different seasons:

1. Winter: Strong offsets between OP and CP fluxes were observed in the period December through February. These differences already amount to 17 gC m$^{-2}$ in the first months of the year (January – February, period 1 in Figure 2 b). In December, the CP shows higher positive fluxes adding another 12 gC m$^{-2}$ to the observed differences (period 5 in Figure 2 b).

2. Transition seasons: During the last months of winter towards spring (March through May, period 2 in Figure 2 b) and in fall (October, period 4 in in Figure 2 b) flux rates between OP and CP generally agree, thus no systematic differences are observed. Accordingly, in this period the offset between the two GAs remains nearly constant.

3. Summer: Large differences arise again during the season from June to September (period 3 in Figure 2 b) with the OP showing higher uptake rates. As a result, the gap in cumulative fluxes between OP and CP steadily increases, summing up to 57 gC m$^{-2}$ for this season.

3.1.2. Application of the self-heating correction scheme

The apparent enhancement in net uptake of CO₂ as measured by the OP is likely to be caused by the self-heating of the instrument linked to the additional heat flux within parts of the optical path disturbing the measurements [Burba et al., 2006; 2008]. The aim of the self-heating correction is to eliminate the self-heating effect of the OP and thus reduce the differences between both GAs.

To analyze the performance of the correction, an orthogonal regression analysis is performed before and after the application of the correction with the intercept representing the offset (Table 3). Different linear relationships between CO₂ fluxes from OP and CP reference during day- and night-time (Table 3) are observed. Therefore $\xi$ fractions were fitted separately for day- and night-time conditions (Table 2). Fitted $\xi$ during day are by a factor of 3 to 7 larger
than during the night. Fitted $\xi$ are tightly linked to the correction approach with $\xi$ varying between 0.1 (Burba_2006) and 0.8 (Burba_2008). This variation is attributed to systematic differences in the formulations, i.e., Eq. (3) and (6). Fitted $\xi < 1$ indicate that with an inclined OP analyzer the required correction is always less than what was suggested for vertically mounted instruments. Intercepts after the self-heating correction stay above zero for the Burba_2006 approach, indicating that there are remaining flux patterns that cannot be corrected for. For the Burba_2008 approach a negative intercept during daytime indicates a significant overcorrection.

To evaluate the performance of the self-heating correction approaches corrected cumulative CO$_2$ budgets were compared to the CP reference (Figure 2). Residual differences remain after the self-heating correction, with gradients of cumulative deviations to the reference varying by season:

1. Winter: For both periods 1 and 5 in Figure 2 b, the self-heating correction approach by Burba_2006 with Eq. (8) has nearly no impact on the fluxes and patterns remain close to the input signal. Under night-time conditions, temperature differences between ambient air temperature and estimated $T_s$ are small with Eq. (8), resulting in a negligible $\xi$ (Table 3) and therefore no substantial self-heating correction. The correction approach with Burba_2008 and Burba_2006 with Eq. (7) yielded good agreement with the CP reference.

2. Transition seasons: During spring (period 2 in Figure 2 b) the self-heating correction approach by Burba_2006 is strongly overcorrecting the CO$_2$ fluxes leading to a cumulative difference of 24 gC m$^{-2}$ in comparison to the CP reference. A slight overcorrection is also found with the Burba_2006 with Eq. (7) approach, while corrected CO$_2$ fluxes with Burba_2006 and Eq. (8) agree with the CP reference. In contrast during fall (period 5 in Figure 2 b) all correcting approaches show comparable results and seem to slightly overcorrect CO$_2$ fluxes.

3. Summer: In period 3 (Figure 2 b), with largest differences between OP and CP (see Section 3.1.1), the Burba_2006 approach, independent of the $T_s$ parametrization, is undercorrecting the CO$_2$ flux with differences of maximal 22 gC m$^{-2}$. The correction approach with Burba_2008 yielded good agreement with the CP reference.

Overall, in 2015 cumulative annual difference to the CP reference are -34, -12 and 51 gC m$^{-2}$ for the self-heating correcting approaches Burba_2008, Burba_2006 with Eq. (7) and Burba_2006 with Eq. (8), respectively. This indicates that independent of the correction approach, the self-heating correction cannot fully remove the offset or is overcorrecting the OP signal. The self-heating correction is only accounting for an overall intercept, capable of removing a net bias while being unable to change the shorter-term flux patterns. Still, even for those cases small seasonal fluctuations remain that lead to non-zero offsets, which may be linked to large seasonal differences between CP and the OP signal, differences between daytime and night-time conditions and also the method itself might be subject to methodological uncertainties (details in Appendix A).

### 3.1.3. Implications of the self-heating correction on CO$_2$ budgets

The approaches that yielded best results on an annual scale (Figure 2 and Section 3.1.2), e.g., Burba_2008 and Burba_2006 with Eq. (7), are used to apply the self-heating correction and offset the self-heating effect of the OP analyzer. With this self-heating correction for the OP, CO$_2$ fluxes are shifted towards less negative and more positive fluxes. Formerly negative or close to zero wintertime CO$_2$ fluxes now show a distinct positive mean value (Figure 3 a and b). In summer, the CO$_2$ loss is increased and therefore the net uptake is reduced. Results
corrected for the self-heating are much closer to the reference CP fluxes (Figure 3 a and b) than results without the application of this additional correction.

Still, systematic discrepancies remain within individual seasons, e.g. in winter some of the weekly mean flux rates remain close to zero or in the negative range, even though absolute values are small. Overall, both approaches of the self-heating correction overcorrect OP fluxes during winter, and undercorrect them in summer (see intercepts in Table 2 and cumulative CO₂ budgets in Figure 3 c and d). The residuals between corrected OP and CP reference during summer and winter partly balance each other for both self-heating correction approaches. With the Burba_2008 approach differences to the CP reference during summer and winter are marginal but annual differences account to 34 gC m⁻², induced by the transition period in spring (Section 2 in Figure 2). In comparison the Burba_2006 approach with Eq. (7) shows higher summer and winter residual but a closer agreement on annual scale (12 gC m⁻²).

### 3.1.4. Components of the self-heating correction approaches

For the application of the self-heating correction a combination of input parameters is required with different magnitudes and seasonal courses. In the discussion to follow, we compared the approaches Burba_2008 and Burba_2006 with Eq. (7) to analyze the relative influence of individual components of the self-heating correction. The self-heating correction in total has a pronounced seasonality (Figure 4 a and b). By separating into individual terms (Figure 4 c and d), it can be demonstrated that single terms can have diverse dynamics over the course of a year.

In both correction approaches the temperature gradient between the ambient air and the surface of the sensor (light blue lines in Figure 4 c and d) is a crucial part. While it is directly implemented in the Burba_2006 approach, it is used to estimate the sensible heat flux in the Burba_2008 approach. The seasonality of the temperature gradient is comparable in both approaches but absolute values differ, because of different offsets in the parameterizations. A second important element of the self-heating correction is focusing on the turbulent conditions. The Burba_2008 approach is using a geometric estimation with the average thickness of the boundary layer (δ, dark blue line Figure 4 c), that stays relatively stable over the course of the year. For the Burba_2006 approach it is represented as the reciprocal of aerodynamic resistance (dark blue line Figure 4 d) with a strong increase in May and decrease in September with quasi-flat stages in-between, strongly influenced by the friction velocity. The third term of the self-heating correction composed of the densities (dark green line in Figure 4 c and d) is slightly different for both approaches, but since there is no notable dynamic in the seasonal course, there is no systematic effect on the overall correction. A seasonality of ξ is caused by the separation into day- and night-time conditions representing summer and winter, respectively. While higher absolute values are found in the Burba_2008 approach the relative changes over the year are similar for both correction approaches (Table 3).

In total, the seasonal dynamic of the Burba_2008 approach results from the temperature gradient and the ξ fraction (Figure 4 a). For the Burba_2006 approach the total correction is dominated in winter by the temperature gradient and the summer maximum is caused by the second term (Figure 4 b). Differences between approaches emerge around March/April, with stable to slightly decreasing tendencies for the total correction with the Burba_2006 approach due to decreasing aerodynamic resistance while the total correction with the Burba_2008 approach is already strongly increasing, causing an strong overcorrecting (see period 2 in Figure 4).
3.2. Heating of sonic anemometer

The scheme based on meteorological conditions (rH and Ta) to control the activation of the sonic anemometer heating worked as planned for the sonic anemometer with controlled-heating and was always switched on when corresponding meteorological threshold conditions were reached. In total 1365 and 849 half-hour intervals with active heating for winter 2013/14 and winter 2015 as well as 6387 and 4449 half-hour intervals without heating for winter 2013/14 and winter 2015, respectively, are observed (Figure 5 a and b). Air temperature during both winter periods is almost always below 1 °C, therefore rH is the driving parameter for controlling the sensor heating. Monthly means for rH, averaged over both winter seasons, are highest during Oct, Nov and Dec (82 %). Accordingly, periods with active heating occur more often during winter 2013/14 covering October, November, December with most humid conditions and active heating for 26–33 % of the time. An exception is April 2015 with large fluctuations in rH, resulting in an overall low mean but activated heating around nearly one quarter of the time.

During the first winter period (2013/14), continuous error messages were observed for both sonic anemometers more or less simultaneously in January 2014 (Figure 5 a). During this time, air temperatures dropped mostly below -40 °C, i.e. outside of the measuring range of the sonic anemometer, thus it cannot be determined if low temperatures or icing of the sensor was triggering these error messages. Therefore the period of January 2014 was excluded and the focus was set to December 2013.

In mid-December 2013 (Figure 5 c), sustained high frequency (around 36000 error messages per half hour) of error messages were observed at the non-heated sonic anemometer, indicating icing of the sensor over duration of several hours. For the same period, at the sonic anemometer with controlled-heating and activated heater error messages are scattered and small (<550 error messages per half hour). This demonstrates that icing has been prevented by the sonic anemometer heating while without this heating ice could build up and disturb instrument performance. We assume that the icing at the non-heated sonic anemometer was eventually removed manually by the site technician, since it appeared only for a very short time period, while meteorological conditions did not change substantially during this event.

In the second winter period (2015) both sonic anemometers showed high error message counts independently from each other. The icing in both cases lasted for a more extensive period (2-3 days) for both the non-heated sonic anemometer and the sonic anemometer with controlled-heating, respectively (Figure 5 d). We hypothesize that the ice buildup event which occurred during activated heating in late January 2015 might have been caused by icing fog introducing rimming. The second ice buildup during the second winter period (mid-February 2015) only occurred at the non-heated sonic anemometer. The previous discontinuous heating at the sonic anemometer with controlled-heating switched off 3 hours before the ice buildup started at the non-heated sonic anemometer. We assume that the heating prevented the initial stages of ice buildup at the heated tower, so even though the heating was not running at the time the ice finally closed around the non-heated sensor, it can be assumed that the active heating made the difference in this case.

3.2.1. Heating effect on sensible heat and momentum fluxes

Without heating, differences in mean Ta averaged for both sonic anemometers, are close to zero with 0.2 °C and -0.3 °C for the first and second winter period, respectively (Figure 6 c and d and see SI Figure S2 c and d). With activated heating, there is a systematic shift in Ta measured by the sonic anemometer with controlled-heating in comparison to the non-heated sonic anemometer (Figure 6 a and b) as well as to the ancillary sensor (see SI Figure S2 a and b). The Ta difference between both sonic anemometers increased slightly over time (first
winter: -1.5 K; second winter: -1.9 K), resulting in a mean $T_a$ reduction of approximately -1.8 K as a consequence of sensor heating.

Differences in the sensible heat flux between both sonic anemometers during periods without heating are close to zero, with median values of -2.9 W m$^{-2}$ and 1.6 W m$^{-2}$ (Figure 6c and d), for the first and second winter period, respectively. With activated heating, sensible heat fluxes tend to increase, with mean offsets of 5.8 W m$^{-2}$ and 4.5 W m$^{-2}$, for the first and second winter period, respectively. Overall, we found an increase in sensible heat fluxes of 5.2 W m$^{-2}$ with activated heating.

Since double axis rotation is applied within the flux-processing software, implications of the sonic anemometer heating on the fluctuations of the vertical wind component can only be investigated by analyzing $\sigma(w)$. Negligible differences between both sonic anemometers are observed with activated (0.002 ± 0.030 m s$^{-1}$ and 0.000 ± 0.030 m s$^{-1}$, as mean ± standard deviation) and without (0.002 ± 0.030 m s$^{-1}$ and -0.002 ± 0.030 m s$^{-1}$, mean ± standard deviation) heating (Figure 6), for the first and second winter period, respectively. Consequently only minor differences of sonic anemometer heating can be found also for the friction velocity with activated (0.02 m s$^{-1}$ and -0.01 m s$^{-1}$) in comparison to conditions without (0.01 m s$^{-1}$ and -0.02 m s$^{-1}$) heating, for the first and second winter period, respectively.

### 3.2.2. Heating effect on the CO$_2$ fluxes

Carbon dioxide flux measurements based on the CP gas analyzing system are not affected by the sonic anemometer heating, i.e. mean CO$_2$ flux offsets between both EC systems with activated (-1.6x10$^{-2}$ µmol m$^{-2}$ s$^{-1}$) and without (-4.1x10$^{-3}$ µmol m$^{-2}$ s$^{-1}$) heating do not differ significantly ($p = 0.9704$, Mann-Whitney test; Figure 7). On the other hand, computing fluxes based on the OP gas analyzing system (corrected for the self-heating of the open-path analyzer by the Burba 2006 approach with Eq. (7)), we observe a more pronounced sonic anemometer heating effect. The mean CO$_2$ flux is significantly ($p < 0.05$, Mann-Whitney test) shifted from 0.02 µmol m$^{-2}$ s$^{-1}$ without heating towards 0.21 µmol m$^{-2}$ s$^{-1}$ with activated heating (Figure 7), resulting in a mean increase in CO$_2$ fluxes of 0.19 µmol m$^{-2}$ s$^{-1}$. There is however no significant difference between CO$_2$ fluxes measured by both CP systems, and thus site differences can be ruled out as a possible explanation. Assuming continuous operation of the sonic anemometer heating, this mean increase in CO$_2$ fluxes would sum up to an additional 30 gC m$^{-2}$ in wintertime efflux over the entire winter season (November – March).

The fact that systematic shifts in fluxes were only observed when calculating fluxes based on OP data suggests an indirect heating effect that can be attributed to the WPL density-flux correction [Webb et al., 1980]. This correction, applied to OP gas analyzers, includes air temperature and sensible heat flux as input data. Accordingly, biases in those will indirectly influence density-corrected OP CO$_2$ fluxes via this correction. In a sensitivity study, we found that the net bias was almost exclusively caused by offsets in sensible heat fluxes, while systematic shifts in the air temperature caused negligible net effects in the CO$_2$ fluxes.

### 4. Discussion

#### 4.1. Self-heating of the open-path LI7500 sensor

The apparent enhancement in net uptake of CO$_2$ with 96 gC m$^{-2}$ as measured by the OP is likely to be caused by the self-heating of the instrument linked to the additional heat flux within parts of the optical path disturbing the measurements [Burba et al., 2006; 2008]. Järvi et al. [2009] determined a 140 gC m$^{-2}$ difference between an OP and CP during roughly two
months (Oct – Dec) for a beech forest site in Finland. However, their data were not gap filled, and the study time frame is very short in comparison to the data presented here. If no reference measurements are present, the potential uptake that may be caused by self-heating of the sensor can be estimated by comparing flux differences between the OP sensor with and without the self-heating correction. Based on this concept, existing studies found differences of 20 gC m\(^{-2}\) [Barrow, Ueyama et al., 2012] and 87 gC m\(^{-2}\) [Atqasuk, Oechel et al., 2014] per year at two Alaskan sites representing similar environmental conditions as our sites near Chersky. Reverter et al. [2011] identified a linear fit between mean annual temperatures and the net effect of the self-heating correction, where the correction effect was clearly elevated at sites situated in cold regions. Applying their suggested approach with a mean temperature of -11 °C found in Chersky [Kittler et al., 2016] suggests a reduction of the CO\(_2\) uptake of 240 gC m\(^{-2}\) through application of the self-heating correction. This apparent over-correction can be explained by the fact that environmental conditions in Chersky (e.g., annual mean temperature and ecosystem type) are far outside the range analyzed by Reverter et al. [2011]. Accordingly, our findings indicate the linear fit between magnitude of the self-heating correction and prevalent temperature cannot be applied across a broad temperature range, and that instead non-linear elements (e.g., wind speed, wind direction and mounting of the analyzer) need to be included when extending the approach by Reverter et al. [2011] to the Arctic domain.

The greatest impact of the self-heating is expected during winter with lowest air temperatures and hence relative highest contribution of the heating effect to the total sensible heat fluxes [Burba et al., 2008; Grelle and Burba, 2007]. This theory is supported by some existing studies that achieved a good agreement between OP and reference measurements during the growing season [Goodrich et al., 2016]. However, other references demonstrate that the self-heating effect is not only affecting fluxes during the cold season, but corrections for sensor self-heating have to be applied to warm season measurements as well [Järv et al., 2009; Ueyama et al., 2012], with different magnitudes in the heating effect [Reverter et al., 2011]. Oechel et al. [2014] found similar seasonal patterns as observed in the presented study, i.e. with high impact of self-heating during both summer and winter seasons, while spring and fall provide just minor contributions to offsets in cumulative flux budgets.

Since different linear relationships between CO\(_2\) fluxes from the OP and the CP can be observed during day- and night-time conditions, the \(\xi\) fractions were fitted separately. The closer agreement during night-time is also reflected by some instrument surface temperature estimations with systematically lower offsets during night-time. Radiative heating over the day and radiative cooling during the night can affect measurements and this effect might be increased under non-vertical OP sensor configurations [Burba et al., 2008] as it is used in this study. This has implication on the fitted \(\xi\) that are an order of magnitude smaller under night-time conditions, compared to the daytime fits. Since our study site is situated in the Arctic, this difference leads to a \(\xi\) fraction seasonality in the overall self-heating correction, because the fractions of day- and night-time vary strongly between summer and winter seasons, respectively.

For all self-heating correction a strong dependency of \(\xi\) on the approach and the parametrization of the instrument surface temperature was demonstrated.

1. In case of the Burba_2008 approach with Eq. (4) and (3), negligible differences in cumulative CO\(_2\) fluxes in comparison to the CP are observed during summer and winter. Annual differences to the CP system are 34 gC m\(^{-2}\), due to an overcorrection during the spring. In general, the Burba_2008 approach represents the most complex structure, dividing the sensor into different sensor elements. The approach was derived for a fully vertical sensor position [Burba et al., 2008] and an adjustment for inclined
sensor mounting is described in Oechel et al. [2014] by tuning the temperature parametrization of the bottom part of the sensor. Here we used a different adjustment by introducing the $\xi$ fraction. Relatively high $\xi$ fractions, for both day- and nighttime conditions with Eq. (4), in comparison to Eq. (5) implying that the correction approach itself can already correct for a large fraction of the sensors self-heating without major tuning, especially under daytime conditions.

2. The Burba_2006 approach with a combination of Eq. (5) and (7) results in negligible differences in comparison to the CP in the annual cumulative CO$_2$ fluxes caused by counteracting tendencies with an overcorrection during winter and an undercorrection during summer. For another study this method with an empirically determined $\xi$ of 0.05 yielded reasonable results [Rogiers et al., 2008]. During night-time, absolute values of $\xi$ fits from the presented study agree with this finding, but under daytime conditions the value is 3-times higher. This difference may be explained by the overall colder temperatures in Chersky, which imply a higher contribution of the self-heating.

3. While the apparent uptake during the Arctic winter is not corrected properly by using the Burba_2006 approach with Eq. (5) and (8), the fitted $\xi$ for daytime is comparable to the one for the Finnish beech forest [Järvi et al., 2009], achieving a good agreement with the reference measurements during the non-winter season. Still, the overall fit of the annual correction is poor within the context of our study.

In general, both correction approaches Eq. (4) with Eq. (3) and Eq. (5) with (7) demonstrated a good performance, depending on the target aim. Annual CO$_2$ budgets yielded best results by applying Eq. (5) with (7) is performing best. If the focus is on correcting CO$_2$ fluxes during the main season e.g. summer and winter, best results were achieved with Eq. (4) with Eq. (3). Thus, further experiments with direct measurements of instrument surface temperature under natural conditions with different instrument configurations are necessary to improve the performance of estimates and reduce uncertainties. Furthermore, we found evidence that self-heating correction in general is influenced by flow patterns indicating that the method is subject to methodological uncertainties that need further investigations.

4.2. Heating of sonic anemometer

Our results demonstrate that the chosen heating scheme can prevent ordinary ice buildup under expected meteorological conditions, and in this way can reduce the power consumptions considerable below that of a continuous or intermittent heating strategy [Goodrich et al., 2016]. Still, there are special meteorological conditions, not being captured with this regular heating scheme, that can cause ice buildup and disturb measurements, like ice fog introducing riming as observed in late January during activated heating. Consequently, the riming should also appear at the unheated tower because of very similar meteorological conditions between sonic anemometers but might have been removed manually before major buildup started. Under this special meteorological situation, ice buildup cannot be anticipated by an activation scheme based on ancillary meteorological conditions. Accordingly, any such scheme to prevent sensor icing must fail.

In both existing studies focusing on the effect of sonic anemometer heating, continuous heating was found to increase the apparent sensible heat flux [Goodrich et al., 2016; Skelly et al., 2002], but a uniform explanation for this effect was not provided. Findings from this study suggest that temperature measurements from the heated sonic anemometer are the driving element for the observed differences in sensible heat fluxes while the wind components only show a minor influence. The most likely explanation of the observed differences in $T_a$ with activated heating is an instrumental issue related to biases in sonic anemometer path lengths, i.e. heating of arms and transducers influences signal runtimes between the transducers. With
an observed reduction in $T_a$ the path length is increased and that effect might be amplified under very cold environmental conditions.

Since no direct heating effect on the variability of the vertical wind speed and the resulting friction velocity was observed, it is also not expected to find a direct heating effect on the determined CO$_2$ mixing ratios and fluctuations. This assumption is confirmed by the finding that the activated heating does not lead to a shift in CO$_2$ fluxes based on the CP gas analyzing system. However, systematic indirect effects can occur when observations during activated heating (sonic temperature, sensible heat flux) are used as input for the WPL density-flux correction of OP flux measurements. In this context, shifts in sensible heat fluxes were found to be the major driver for a biased WPL-correction when sonic anemometer heating is activated. The sonic anemometer heating holds the potential to significantly alter the seasonal CO$_2$ budget indirectly through biasing the WPL density-flux correction. The observed mean bias in CO$_2$ fluxes with active heating of this study is a magnitude larger than the overestimation reported by Goodrich et al. [2016] with $-0.03$ µmol m$^{-2}$ s$^{-1}$. The mean bias was found to be caused by a higher variance in the vertical wind component having a direct effect on the determined fluxes of CO$_2$ with a CP and the same type of sonic anemometer as used in this study [Goodrich et al., 2016].

4.3. Relevance of wintertime CO$_2$ budgets

At the site close to the city of Chersky that has been investigated in the context of this study, appropriately corrected wintertime emissions amount to about 30 gC m$^{-2}$. These net emissions are relatively low compared to the substantial net releases of CO$_2$ during wintertime which have been reported across different Arctic permafrost ecosystems like wet sedge (115 gC m$^{-2}$), heath [99 gC m$^{-2}$, both Euskirchen et al., 2012], or forest tundra [89 gC m$^{-2}$, Zimov et al., 1996], all representing 3 years of measurements covering a period from September–April/May. Assuming a temperature dependence of winter CO$_2$ flux as suggested by e.g. Zimov et al. [1996], shorter study time frames focusing on e.g. just the core winter period might lead to smaller winter effluxes. Such results were presented e.g. by Oechel et al. [2014] with 12 gC m$^{-2}$ covering a period from October to April for a moist acidic tundra, or Lüers et al. [2014] with 6 gC m$^{-2}$ during November to April for a semi-desert ecosystem. Given that the largest portion of wintertime CO$_2$ emissions observed at our site near Chersky can be attributed to the fall shoulder season and the transition into early winter, our observations generally agree with these findings, but also indicate slightly higher efflux at the peak of polar winter than found at both of the other sites with continuous permafrost [Lüers et al., 2014; Oechel et al., 1997].

Since net CO$_2$ emissions during Arctic winter can sum up to a substantial portion of the growing season budget, correcting the self-heating of the open-path LI7500 gas analyzer, and accounting for potential biases linked to the active heating of the sonic anemometer both are essential elements in the EC flux processing protocol to obtain high quality annual budgets of CO$_2$ fluxes. In particular, neglecting the self-heating correction of the open-path gas analyzer would lead to a systematic low bias in wintertime emission estimates, and accordingly would yield annual flux budgets with exaggerated net CO$_2$ uptake by the ecosystem [Oechel et al., 2014]. With future increases in Arctic temperatures expected particularly outside the growing seasons, it can be speculated that unfrozen soils will provide suitable conditions for decomposition of organic material for extended periods under future climate change, therefore further elevating the role of wintertime fluxes for annual CO$_2$ budgets. High-quality flux observations under the extreme conditions of polar winter are therefore essential for both assessing the role of Arctic ecosystems as net sources or sinks for greenhouse gases as well as for allowing a reliable quantification of changes in greenhouse gas fluxes as a consequence of climate change.
5. Conclusions

In this study, we quantified the effect of different heating systems to achieve high quality year-round EC CO₂ fluxes in cold environments. The first part focused on the correction of the self-heating effect of the open-path gas analyzer, while the second part deals with the effect of the sonic anemometer heating on the determined scalars and fluxes. Based on our analyses of three years of continuous EC measurements from a site close to the city of Chersky, measures to avoid heating biases were developed, resulting in appropriately corrected wintertime emissions of about 30 gC m⁻². The methods we developed to avoid biases of instrument LI-7500 self-heating and controlled sonic anemometer heating on flux data quality were the following:

1. A self-heating correction for CO₂ fluxes based on the LI-7500 gas analyzer is essential to avoid systematic biases in long-term budgets. For an inclined sensor setup, not the full self-heating correction as proposed by Burba et al. [2008] needs to be applied.

2. Strongest self-heating biases in LI-7500 flux data were found not only in winter but also during the summer, while shoulder seasons were largely unaffected. Accordingly, self-heating correction not only needs to be applied for cold-season observations, but is also essential for summertime CO₂ fluxes. Therefore a year-round application of self-heating correction is necessary to avoid systematic bias on annual flux budgets.

3. Sonic anemometer heating affects measurements of sonic temperature and sensible heat fluxes, but no direct effect on the variability of the vertical wind speed and the resulting friction velocity was observed.

4. CO₂ fluxes based on a CP gas analyzer are unaffected by sonic anemometer heating, and longer heating periods are likely to have a positive effect on the data quality of these fluxes. A small but systematic indirect bias of sonic anemometer heating on CO₂ flux data occurs through the application of the WPL density-flux correction for open-path analyzers, since this correction scales with the sensible heat flux, which is biased when the heating is activated. For the OP fluxes a shorter but recurring application of heat pulses to avoid icing of the sensor may prove beneficial for eddy covariance flux data quality in cold climates, particularly if icing fog events can occur.

We recommend a sonic anemometer heating scheme for Arctic conditions that is not controlled by meteorological conditions, but instead either is activated at regular intervals independent of prevailing weather conditions, or use extended heating periods up to permanent heating. For the first option possible solutions might be to activate the sonic anemometer heating for an hour per day in staggered cycles to avoid preferentially exclusion of a specific period while removing potential icing to guarantee high quality measurements. However, a strong disturbance of the observed turbulent fluxes takes place during activation/deactivation periods of the sonic anemometer heating, so these transition periods need to be flagged as lowest data quality, and discarded from further flux data analysis. If an OP system is used, CO₂ fluxes should be treated with caution due to the indirect heating effect of the sonic anemometer. Accordingly, to avoid systematic biases in the OP CO₂ budget, either an alternative data source for the sensible heat flux (e.g. ancillary instrumentation, or gap-filling) needs to be used as input for the WPL density-flux correction, or a suitable correction procedure to minimize the systematic offsets in sensible heat fluxes during sonic anemometer heating periods should be applied.

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We applied first-last-author-emphasis and equal-contribution (alphabetical sequence) methods for the order of authors [Tscharnke et al., 2007]. We thank one anonymous referee and Georg Burba for their valuable feedback and helpful comments and suggestions that strongly improved our manuscript.

Data are available from the European Fluxes Database Cluster (http://www.europe-fluxdata.eu/home), site-code “RU-Ch2”, with following options for the CO2 flux: open-path gas data without the self-heating correction, open-path data with the self-heating correction and closed-path data.

Appendix

Sensor geometry might be a crucial component if the OP sensor is mounted in an inclined position (Figure A1 a), while it should be independent for vertically oriented instruments [Burba et al., 2008]. For different directions of the horizontal wind, heated air might be blown further into (Figure A1 b) or out of (Figure A1 c) the optical path, with potential consequences for the impact of the self-heating effect, and therefore also on the necessary correction. To investigate the dependence of $\xi$ on the wind field properties Eq. (5) with Eq. (7) was reorganized to determine $\xi$ directly for each half-hour interval and subsequently deriving statistics on the dependence of the $\xi$ fraction for certain wind direction and wind speed classes. Since this approach does not account for nonlinear dependencies by minimizing the sum of squared residuals, values can vary systematically in comparison to the optimization approach. Accordingly, this analysis will only be used to identify how the sensor geometry and the angle of attack can influence the self-heating correction.

To investigate the dependence of the sensor geometry and wind fields on the self-heating correction, $\xi$ was computed individually for each 30-minute interval (N > 5000, mean = 0.15, standard deviation = 0.39). Wind field properties summarized over the annual cycle 2015 (see SI Figure S3) indicate a dominating SE (150°) wind directions and a mean wind speeds of 3.8 m s⁻¹. Analyzing the resulting set of $\xi$ in dependence of the wind conditions reveals distinct structures (Figure A2) that hint at an influence of the flow pattern on the self-heating effect. The fraction $\xi$ is generally smallest within the SE sector (0.12 ± 0.28) followed by NE (0.13 ± 0.46), SW (0.16 ± 0.38) and highest values are observed in NW (0.22 ± 0.47). Under low wind speed conditions (e.g., around 300° in Figure A2) $\xi$ tends to be highest.

The OP sensor was installed in an inclined position by ~15° towards ESE (120°). Accordingly, with horizontal wind coming from the NW sector (240° – 360°), air will be blown directly into the optical path, reinforcing the self-heating effect (Figure A1 b). In contrast, the extra heat flux induced by the instrument self-heating will be transported out of the optical path with wind directions from the SE (60° – 180°, Figure A1 c). Focusing on the lower wind speeds (< 4 m s⁻¹), this pattern can be observed in Figure A2: comparatively small $\xi$ are fitted for the E-SE sectors, indicating that the self-heating effect within these directions is smaller than average. In contrast, winds from the W-NW sectors can be associated with higher-than-average $\xi$, suggesting that heated air is directed into the optical path and leads to an amplified self-heating effect. For higher wind speeds (> 4 m s⁻¹), we assume that the
associated increase in mechanical turbulence generates a better mixing of the air around the sensors, therefore reducing the relative impact of the self-heating effect, and accordingly also the required $\xi$ to correct the fluxes. This can be seen in Figure A2 for almost all directions, except for the SW sector ($190^\circ - 230^\circ$): For these directions, flow distortion by the sonic anemometer [Göckede et al., 2008; Mauder et al., 2007] under high wind speeds appears to influence the performance of the OP sensor, leading to highly elevated $\xi$ that are unlikely to be caused by the instrument self-heating alone.

We found evidence that self-heating correction is influenced by flow patterns. Results presented here are used as a case study, since findings are not reproducible with the Burba 2008 approach. This indicates methodological uncertainties that need further investigations.

References


Burba, G. G., D. K. McDermitt, A. Grelle, D. J. Anderson, and L. Xu (2008), Addressing the influence of instrument surface heat exchange on the measurements of CO$_2$ flux from open-


Zimov, S. A., S. P. Davidov, Y. V. Voropaev, and S. F. Prosiannikov (1993), Planetary Maximum CO2 and Ecosystems of the North, paper presented at Carbon Cycling in Boreal Forest and Sub-arctic Ecosystems: Biospheric Responses and Feedbacks to Global Climate Change, Department of Civil Engineering, Oregon State University, Corvallis, Oregon.

Table 1. Quality flag (QF) of EC CO$_2$ fluxes as percentage of winter season (November–April) measurements from both sites according to Foken et al. [2005] and [2012].

<table>
<thead>
<tr>
<th>Site</th>
<th>Winter season</th>
<th>QF 1-3 [%]</th>
<th>QF 1-6 [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tower 1</td>
<td>2013/14</td>
<td>23.2</td>
<td>47.2</td>
</tr>
<tr>
<td></td>
<td>2014/15</td>
<td>21.8</td>
<td>60.9</td>
</tr>
<tr>
<td></td>
<td>2015/16</td>
<td>19.2</td>
<td>55.1</td>
</tr>
<tr>
<td>Tower 2</td>
<td>2013/14</td>
<td>18.5</td>
<td>44.2</td>
</tr>
<tr>
<td></td>
<td>2014/15</td>
<td>21.9</td>
<td>55.6</td>
</tr>
<tr>
<td></td>
<td>2015/16</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2. Additional formulations to correct for the self-heating of an open-path LI7500 gas analyzer as described in Burba et al. [2008].

Description | Formulation
--- | ---
S as sensible heat flux after Nobel [1983] with $r^{top}$ is 0.0225 m and $r^{spar}$ is 0.0025 m

$S^{bot} = k_{air} \frac{T^{bot}_{s} - T_a}{\delta^{bot}}$

$S^{top} = k_{air} \frac{(r^{top} + \delta^{top})(T^{top}_{s} - T_a)}{r^{top}\delta^{top}}$

$S^{spar} = k_{air} \frac{(T^{spar}_{s} - T_a)}{r^{spar}\ln\left(\frac{r^{spar} + \delta^{top}}{r^{spar}}\right)}$

$\delta$ as average thickness of the boundary layer above the window with $l^{bot}$ is 0.065 m, $l^{top}$ is 0.045 m and $l^{spar}$ is 0.005 m

$\delta^{bot} = 0.004 \sqrt{\frac{l^{bot}}{u}} + 0.004$

$\delta^{top} = 0.0028 \sqrt{\frac{l^{top}}{u}} + \frac{0.00025}{u} + 0.0045$

$\delta^{spar} = 0.0058 \sqrt{\frac{l^{spar}}{u}}$

$T_s$ [K] as the instrument surface temperature with $T_0$ is 273.15

$T_{s, day}^{bot} = 0.944 (T_a - T_0) + 2.57 + T_0$

$T_{s, night}^{bot} = 0.883(T_a - T_0) + 2.17 + T_0$

$T_{s, day}^{top} = 1.005 (T_a - T_0) + 0.24 + T_0$

$T_{s, night}^{top} = 1.008 (T_a - T_0) - 0.41 + T_0$

$T_{s, day}^{spar} = 1.01 (T_a - T_0) + 0.36 + T_0$

$T_{s, night}^{spar} = 1.01 (T_a - T_0) - 0.17 + T_0$
Table 3. Overview of results from non-linear fit for the fraction $\xi$ with Burba et al. [2008] as Eq. (4) with Eq. (3), Burba et al. [2006] as Eq. (5) with Eq. (7) and Burba et al. [2006] as Eq. (5) with Eq. (8). Slope and intercepts are obtained from orthogonal regression analysis, $CP = \text{Intercept} + \text{Slope} \cdot \text{OP}$. Values in parentheses indicate the 95% confidence interval of the parameter estimates obtained for slope and intercept. Pearson’s correlation coefficients ($r$) are given in the last column. Data cover 2 full annual cycles from April 2014–2016.

<table>
<thead>
<tr>
<th>Time of day</th>
<th>Self-heating correction approach</th>
<th>$\xi$</th>
<th>Intercept [μmol m$^{-2}$ s$^{-1}$]</th>
<th>Slope [μmol m$^{-2}$ s$^{-1}$]</th>
<th>$r$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day-time</td>
<td>no correction</td>
<td>-0.427 (-0.459 – -0.396)</td>
<td>1.111 (1.100 – 1.122)</td>
<td>0.96</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Burba_2008</td>
<td>0.806 ± 0.017</td>
<td>0.247 (0.201 – 0.294)</td>
<td>1.084 (1.067 – 1.101)</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>Burba_2006 with Eq. (7)</td>
<td>0.130 ± 0.004</td>
<td>-0.061 (-0.113 – -0.007)</td>
<td>1.115 (1.095 – 1.135)</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>Burba_2006 with Eq. (8)</td>
<td>0.077 ± 0.002</td>
<td>-0.066 (-0.118 – -0.013)</td>
<td>1.121 (1.101 – 1.140)</td>
<td>0.97</td>
</tr>
<tr>
<td>Night-time</td>
<td>no correction</td>
<td>-0.297 (-0.327 – -0.268)</td>
<td>1.242 (1.210 – 1.278)</td>
<td>0.81</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Burba_2008</td>
<td>0.294 ± 0.026</td>
<td>-0.150 (-0.215 – -0.100)</td>
<td>1.214 (1.141 – 1.292)</td>
<td>0.83</td>
</tr>
<tr>
<td></td>
<td>Burba_2006 with Eq. (7)</td>
<td>0.042 ± 0.003</td>
<td>-0.129 (-0.196 – -0.067)</td>
<td>1.214 (1.139 – 1.295)</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
<td>Burba_2006 with Eq. (8)</td>
<td>0.011 ± 0.006</td>
<td>-0.264 (-0.328 – -0.204)</td>
<td>1.179 (1.107 – 1.256)</td>
<td>0.82</td>
</tr>
</tbody>
</table>
**Figure 1.** Time frames and used data for different analyses. Data coverage with QF 1-3.

**Figure 2.** Comparison of cumulative CO₂ fluxes for the CP (black) and OP (grey) systems and different approaches of the self-heating correction for the OP (colored lines) calculated for a full year (a) and per season (b).

**Figure 3.** Weekly averaged fluxes (a and b) with mean flux rates (top center as mean ± standard deviation [µmol m⁻² week⁻¹]) and cumulative budgets (c and d) with seasonal budgets ([gC m⁻²]), with number representing seasonal budgets with corresponding color coding. Left panels give results for the summer season 2015 (June–October) and the right panels for the following winter 2015/16 (November–March). Note that axes for summer and winter are different due to systematically different flux rates for each season.

**Figure 4.** Monthly means for self-heating correction approaches Burba_2008 (left) and Burba_2006 (right) in total (top) and for individual terms with a logarithmic scaling (bottom). The legend on top described the color coding in the corresponding bottom panel. The seasonal variability of the fraction ξ is caused by the varying proportions of day- and night-time over the course of the year, since the values optimized for daytime conditions are significantly higher than those for night-time. For the Burba_2008 approach only the parametrization from the bottom part of the sensor is used, because the top and spars section only have a marginal influence on the overall correction.

**Figure 5.** Heating periods (grey bars) and recorded error messages from the sonic anemometers (red and blue symbols) during both winter seasons. The vertical size of the gray bars depicts the fraction of each half-hour interval with activated heating (right axis), and symbols show the number of error messages (left axis) at the sonic anemometer with controlled-heating (red symbols) and at the non-heated sonic anemometer (blue symbols). Lower panels (c and d) focus on a more detailed period that is marked with black bars in the top panel (note changes of the y-axis from logarithmic to linear scale from the top to the lower panel).

**Figure 6.** Comparison of differences of air temperature ($T_a$, purple), variance of the vertical wind speed ($\sigma^2(v)$, blue), sensible heat flux ($H$, green) and friction velocity ($u_*$, orange) retrieved from the sonic anemometer for both winter periods (a and c for the first winter season and b and d for the second winter season) with activated (a and b) and without (c and d) heating. Total number of data (N) and bandwidth (bw) of the kernel density estimation for each variable and heating-case are given in corresponding colors in each sub-plot. Note that each variable has its own color-corresponding x-axis and that ranges between x-axes differ. Densities were normalized by their range. Vertical lines indicate means.

**Figure 7.** Comparison of NEE differences from the OP (purple, representing the first winter season 2013/14) and CP (blue, representing the second winter season 2015) between heated (a) and unheated (b) conditions. Total number of data (N) and bandwidth (bw) of the kernel density estimation for each variable are given in corresponding colors in each sub-plot.

**Figure A1.** Conceptual overview of a potential wind direction impact on the self-heating effect for inclined OP sensors. We separate calm conditions (a) from conditions when the heated air is blown into (b) or away from (c) the measurement path. Red shaded area mark the volume within the measurement cell that is influenced by the heating and the black curved arrow the heat flux direction.
Figure A2. Averaged fraction $\xi$ (color coded) binned by wind direction ([$^\circ$], black compass rose) and wind speed ([m s$^{-1}$], grey dashed circles). For the instrument surface temperature estimation Eq. (7) was used. The focus is set to small wind speeds up to 4 m s$^{-1}$ with semi-transparent colors for higher wind speeds. The OP sensor is 15$^\circ$ towards ESE indicated by the black dashed line.
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