

# Geophysical Research Letters



## RESEARCH LETTER

10.1029/2020GL092256

### Key Points:

- High levels of CO<sub>2</sub> exchange during the Arctic winter, associated with high wind speeds, have a marked effect on the annual carbon budget
- Conventional flux measurement and calculation techniques are subject to large uncertainties under Arctic low-flux conditions
- Local abiotic processes cannot explain the high-flux events, suggesting advective flux contributions or unidentified instrumental limitations

### Supporting Information:

Supporting Information may be found in the online version of this article.

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### Citation:

Jentzsch, K., Schulz, A., Pirk, N., Foken, T., Crewell, S., & Boike, J. (2021). High levels of CO<sub>2</sub> exchange during synoptic-scale events introduce large uncertainty into the Arctic carbon budget. *Geophysical Research Letters*, 48, e2020GL092256. <https://doi.org/10.1029/2020GL092256>

Received 22 DEC 2020

Accepted 20 APR 2021

## High Levels of CO<sub>2</sub> Exchange During Synoptic-Scale Events Introduce Large Uncertainty Into the Arctic Carbon Budget

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**Abstract** CO<sub>2</sub> release from thawing permafrost is both a consequence of, and a driver for, global warming, making accurate information on the Arctic carbon cycle essential for climate predictions. Eddy covariance data obtained from Bayelva (Svalbard) in 2015, using well-established processing and quality control techniques, indicate that most of the annual net CO<sub>2</sub> uptake is due to high CO<sub>2</sub> flux events in winter that are associated with strong winds and probably relate to technical limitations of the gas analyzer. Emission events may relate to either (unidentified) instrumental limitations or to physical processes such as CO<sub>2</sub> advection. Excluding the high winter uptake events yields an annual CO<sub>2</sub> budget close to zero; whether or not these events are included can, therefore, have a considerable effect on carbon budget calculations. Further investigation will be crucial to pinpoint the factors causing these high CO<sub>2</sub> flux events and to derive scientifically substantiated flux processing standards.

**Plain Language Summary** Global warming is making Arctic soils thaw, with formerly frozen organic material decomposing and producing the greenhouse gas CO<sub>2</sub>. This CO<sub>2</sub> release further amplifies the rise in temperature. In order to predict how our climate will develop in the future, we, therefore, need to investigate how much CO<sub>2</sub> is released into the atmosphere and how much is taken up by plants. Strong CO<sub>2</sub> release or uptake signals are not expected during the Arctic winter due to the reduced microbial and plant activity but have nevertheless been observed at Arctic sites. We have investigated CO<sub>2</sub> exchanges during the winter of 2015 at the Bayelva site, Svalbard, using the eddy covariance technique. We found that high levels of CO<sub>2</sub> emission and uptake occurred during periods with high wind speed and have a significant impact on the calculated net annual CO<sub>2</sub> exchange. The apparent CO<sub>2</sub> uptake is likely to be an artefact resulting from technical limitations of the instruments, while the high levels of CO<sub>2</sub> emission are probably a result of physical processes. However, known physical mechanisms alone, such as episodic outbursts of CO<sub>2</sub> stored within the snow, cannot adequately explain our observations. Additional measurements will be required to identify the processes at play.

## 1. Introduction

It has been estimated that 1,662 Tg C (in the form of the greenhouse gas CO<sub>2</sub>) are emitted into the atmosphere every winter from northern permafrost soils (Natali et al., 2019). Since the release of CO<sub>2</sub> from thawing permafrost is both a consequence of and a driver for global warming; such quantification of the large-scale net exchange of CO<sub>2</sub> is a crucial prerequisite for accurate climate prediction. But what data are such estimates based on? One approach for quantifying carbon losses from the northern permafrost region is to synthesize and upscale in situ CO<sub>2</sub> flux observations (e.g., Belshe et al., 2013; McGuire et al., 2012; Natali et al., 2019). However, this approach is subject to a number of issues that can result in considerable uncertainties in the final data. These issues include a low measurement density in the Arctic region despite the high spatial variability of CO<sub>2</sub> fluxes, discrepancies between different flux measurement techniques, and the absence of any unified data processing, filtering, and gap-filling standards. At best, these issues can cause random uncertainties that cancel each other out if the samples are large enough, but a bias could also be introduced into large scale quantifications of the Arctic carbon cycle if unexplained fluxes are included in, or excluded from, individual flux time series without sufficient justification. Because our

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understanding of the physical processes controlling CO<sub>2</sub> exchange in winter is limited, unexplained winter fluxes are often ignored. For example, Natali et al. (2019) ignored not only negative monthly winter fluxes indicating CO<sub>2</sub> uptake, but also any inexplicably large winter fluxes exceeding 2 g C m<sup>-2</sup> d<sup>-1</sup>. Both negative and anomalously high positive CO<sub>2</sub> fluxes have, however, been observed in eddy covariance (EC) measurements from several high-latitude sites and these have been shown to have a significant effect on the annual carbon budget (e.g., Lüers et al., 2014; see also Amiro, 2010; Hirata et al., 2005; Kittler et al., 2017; Lafleur & Humphreys, 2008; Ono et al., 2007). A range of interpretations have been put forward to explain these unexpected flux measurements. Physical explanations, such as the episodic releases of CO<sub>2</sub>-enriched or depleted air from snow pores known as pressure-pumping (Massman & Lee, 2002; Massman et al., 1997) or from an air layer beneath the measurement height (Aubinet et al., 2012; Schaller et al., 2019), contrast with explanations involving methodological or technical shortcomings of the EC method in cold, low-flux environments (e.g., Butterworth & Else, 2018; Kittler et al., 2017). Depending on which interpretation is accepted, some of the studies retain the unusual flux estimates while others reject them as physically impossible and, therefore, erroneous.

In this study, we hypothesize that the unsubstantiated exclusion of currently unexplained wintertime high-flux CO<sub>2</sub> exchange events might introduce a considerable bias into a site's annual carbon budget. We aim to address the following questions:

- How much do such events contribute to a site's annual carbon budget?
- What are the main characteristics of these events and under what environmental conditions do they typically occur?
- Can the events be explained by physical mechanisms, or are they artefacts relating to methodological or technical problems in the measurement setup?

We have analyzed half-hourly CO<sub>2</sub> fluxes recorded over a 12-month period at a research site on Svalbard in 2015, focusing in particular on strong CO<sub>2</sub> exchange events during the winter months. Because Svalbard is located within a boundary zone between cold Arctic air from the north and mild maritime air from the south it is subject to large fluctuations in weather conditions, particularly in winter when the temperature contrast between the two air masses is greatest (Førland et al., 1997).

## 2. Materials and Methods

### 2.1. Site Description

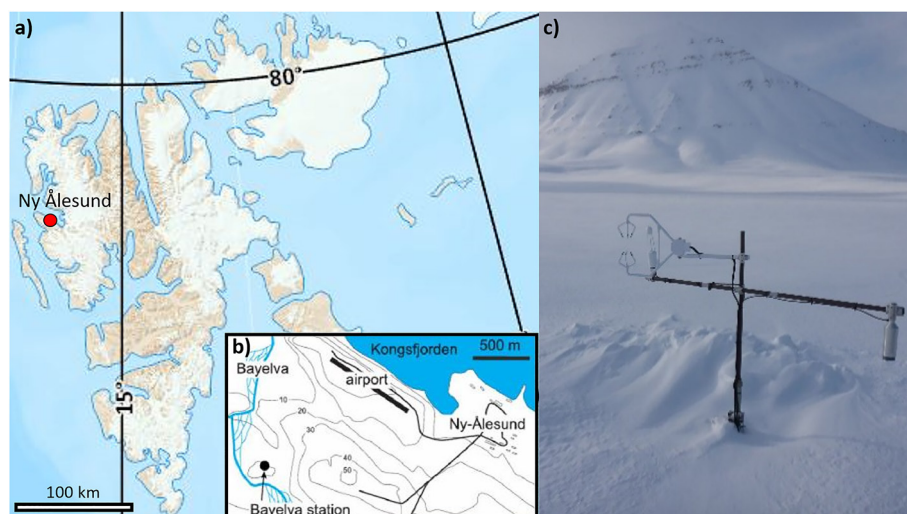
Our study site lies within the Bayelva River catchment area (Text S1), about 2 km west of the Ny-Ålesund research base on the island of Spitsbergen (Figures 1a and 1b). The area is characterized by a maritime climate with cool summers and, considering its latitude, relatively mild winters. Snow typically accumulates in September/October and melts in June/July. In 2015, the maximum snow cover (0.9 m) occurred in March; it had all melted by mid-June and then started to accumulate again in mid-October.

The site comprises a permafrost and climate monitoring station (operational since 1998) located at 78°55'15.4"N and 11°49'59.6"E on Leirhaugen hill, with an EC system (operational from 2007 to 2017; Figure 1c) located at 78°55'17.9"N and 11°49'51.6"E on its northwestern slope (<5° inclination).

### 2.2. Measurements

The CO<sub>2</sub> and energy fluxes were calculated from EC measurements. The setup comprised a Campbell Scientific CSAT3 sonic anemometer and a Licor Biosciences LI-7500A open-path infrared gas analyzer, recording at a frequency of 20 Hz. Both instruments were mounted on a mast at a height of 2.75 m above the snow-free ground (Figure 1c).

In addition to the flux data, our analyses made use of meteorological data from the Bayelva climate monitoring station, available at a half-hourly resolution (Boike et al., 2018) as well as manual measurements of the snow density and the CO<sub>2</sub> concentration within the air-filled snow pores, acquired in May 2016 (Table S1).



**Figure 1.** (a) Location of Ny-Ålesund on Svalbard (Norwegian Polar Institute, n.d.). (b) Location of the study site in the Bayelva river catchment, close to Ny-Ålesund. Thick black lines mark roads and contour lines give the height in meters (adapted from Westermann et al., 2009). (c) View of the eddy covariance system in April 2014 (photo by S. Frey, AWI), facing west.

### 2.3. Data Processing and Analysis

We used the open-source EddyPro 7 software (LI-COR Inc., 2017) to calculate the half-hourly turbulent fluxes of CO<sub>2</sub>, sensible heat, latent heat, and momentum from the high frequency EC measurements recorded in 2015 and filtered the resultant time series using well-established quality criteria (Foken et al., 2012; Text S2).

Our investigations focused on the strong CO<sub>2</sub> exchange events during the winter of 2015, when CO<sub>2</sub> uptake by the ground due to photosynthesis can be assumed to have been negligible (Figure S1). Following Schaller et al. (2019), we applied a median absolute deviation test (Hoaglin et al., 2000) to detect periods of unusually high levels of CO<sub>2</sub> flux during the winter months (Text S3).

To infer the impact of these high CO<sub>2</sub> flux events on the site's annual carbon budget we calculated the net annual exchange of CO<sub>2</sub>. We bridged small gaps (usually less than two days, but with one 5-day gap in December) by linear interpolation. Fluxes during a large data gap from 1 to 13 January in 2015 were set to zero.

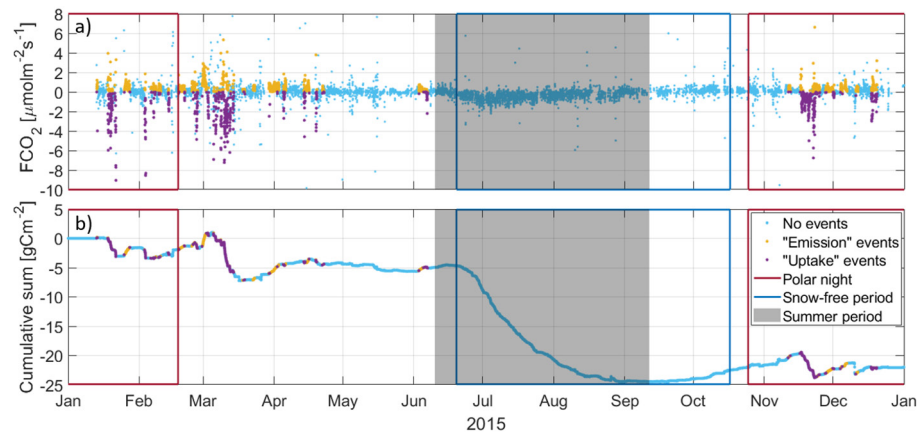
We assessed the quality of the flux estimates that remained after filtering, using statistical quality criteria and spectral analysis and by testing the sensitivity of the final flux estimates to changes in the processing methods and in the applied flux corrections (Text S2).

To quantify the possible contribution of wind-induced pressure-pumping to the observed fluxes, we estimated the maximum amount of CO<sub>2</sub> that could be released from snow pores during periods of high wind velocity, based on the snow density and the CO<sub>2</sub> concentration inside snow pores obtained from sporadic manual measurements and also taking into account automated measurements of snow depth and the snow dielectric constant during the events (Text S4).

## 3. Results

### 3.1. Contributions of Events to the Annual Carbon Budget and Event Characteristics

We identified 52 events with apparently high levels of CO<sub>2</sub> exchange, in total covering about 15% of the winter period (Figure 2a). During these events the half-hourly CO<sub>2</sub> fluxes showed a characteristic temporal development, with the absolute CO<sub>2</sub> fluxes increasing until they reached a maximum peak or plateau, and then dropping back to their starting values (see an example in Figure 3a). The events persisted over periods ranging from a few hours to four days, with a median duration of about 17 h (Figure S2a). In 80%



**Figure 2.** (a) Time series of half-hourly CO<sub>2</sub> fluxes (FCO<sub>2</sub>) at Bayelva in 2015, showing the detected events with apparently high levels of CO<sub>2</sub> uptake or emission. Positive fluxes indicate CO<sub>2</sub> release into the atmosphere and negative fluxes indicate CO<sub>2</sub> uptake into the ground. (b) Event times superimposed on the cumulative sum of the flux time series. The summer period, which was defined as the period during which the running monthly mean of CO<sub>2</sub> fluxes remained consistently below zero (indicating a net CO<sub>2</sub> uptake by the ecosystem), was excluded from the event analysis. The “snow-free” period is the period during which there was no snow cover over the ground.

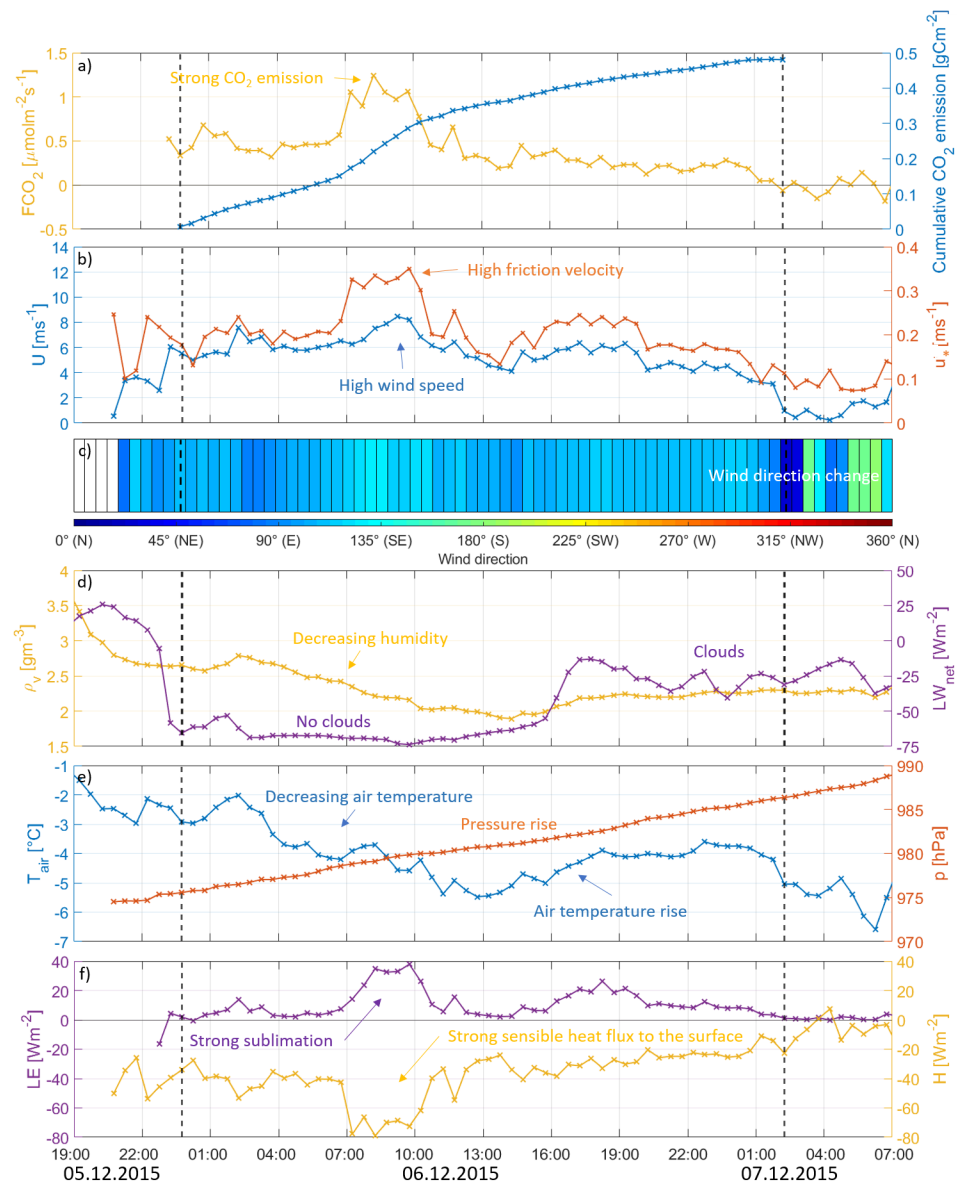
of the cases, the interval between two events was less than one day (Figure S2b). Peak CO<sub>2</sub> fluxes during these events ranged between  $-9.0 \mu\text{mol m}^{-2} \text{s}^{-1}$  (uptake) and  $3.2 \mu\text{mol m}^{-2} \text{s}^{-1}$  (emission; Figure S2c), far exceeding the approximately  $2 \mu\text{mol m}^{-2} \text{s}^{-1}$  amplitude of seasonal variations (Figure 2a). The total net CO<sub>2</sub> exchange during an individual event ranged from an uptake of  $-3.6 \text{ g C m}^{-2}$  per event to an emission of  $2.2 \text{ g C m}^{-2}$  per event, with an average absolute net exchange of  $0.56 \text{ g C m}^{-2}$  per event (Figure S2d). During the 51 days of accumulated CO<sub>2</sub> flux events, a net amount of  $-6 \text{ g C m}^{-2}$  was taken up by the ground. This is almost 30% of the total net CO<sub>2</sub> uptake of  $-21 \text{ g C m}^{-2}$  over the whole of 2015 (Figure 2b). The net flux during the events consisted of 34.5 days with CO<sub>2</sub> emissions totaling  $16 \text{ g C m}^{-2}$  and 16.5 days with CO<sub>2</sub> uptakes totaling  $-22 \text{ g C m}^{-2}$ .

### 3.2. Meteorological Conditions During the Events

Our analyses revealed that the high CO<sub>2</sub> flux events were associated with a change in the synoptic-scale forcing (i.e., the passage of a frontal system), characterized by high wind speeds and distinct changes in meteorological variables such as wind direction, atmospheric pressure, air temperature, humidity, and downwelling longwave radiation (see an example in Figures 3b–3e and Figures S3 and S4), the latter being an indicator of cloudiness. We identified a positive correlation between large absolute CO<sub>2</sub> fluxes and high wind speed, especially where wind speed exceeded  $8 \text{ m s}^{-1}$ . High wind speed during the identified events also increased the turbulent energy fluxes. Strong downward sensible heat fluxes of up to  $-160 \text{ W m}^{-2}$  amplified sublimation at the snow surface, at the same time resulting in increased upward latent heat fluxes of up to  $143 \text{ W m}^{-2}$  (see an example in Figure 3f, and in Figures S5a and S5b). We observed that uptake events occurred predominantly when the net longwave radiation was close to zero and the relative humidity was high, indicating the presence of low-level clouds or fog (Figure 4 and Figure S6).

### 3.3. Flux Quality During the Events

Apart from the standard quality criteria (Section 2.3; Text S2), we also introduced white noise contamination as an additional quality criterion for the flux estimates. We defined those spectra that showed an increase in the spectral energy of the fluxes between 1 and 4 Hz, as well as between 4 and 10 Hz where the energy should normally be decreasing according to the Kolmogorov law (Wyngaard, 2010), as having been affected by excessive white noise. While we could not identify any serious quality issues relating to the event flux measurements using the standard quality criteria, our spectral analyses revealed that when the net longwave radiation was close to zero (Figure 4e) and the relative humidity high (Figure 4f), most of the

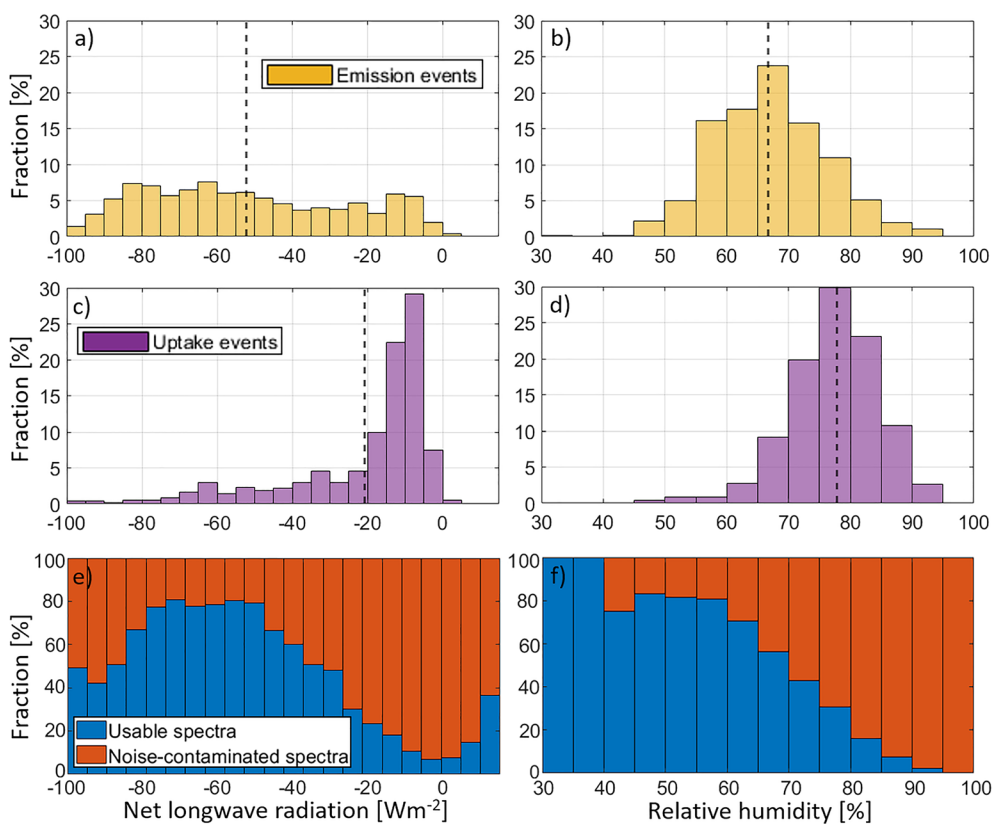


**Figure 3.** Overview of meteorological conditions during an emission event. The beginning and end of the event are marked by black dashed lines. The illustration includes (a) CO<sub>2</sub> fluxes ( $FCO_2$ ) and cumulative CO<sub>2</sub> emission, (b) wind speed ( $U$ ) and friction velocity ( $u_*$ ), (c) wind direction, (d) absolute humidity ( $\rho_v$ ) and net longwave radiation ( $LW_{net}$ ; negative value = energy loss from the surface to the atmosphere), (e) air temperature ( $T_{air}$ ) and atmospheric pressure ( $p$ ), as measured 2 m above the ground, and (f) latent heat flux ( $LE$ ) and sensible heat flux ( $H$ ). Note that the two vertical axes in both (a) and (b) have different scales. For an example of meteorological conditions during an uptake event see Figure S7.

spectra of CO<sub>2</sub> concentration fluctuations were strongly affected by white noise contamination. Adopting this noise contamination as an additional quality criterion (Figure S8) resulted in 90% of the fluxes during apparent CO<sub>2</sub> uptake events being removed from the time series. This then reduced the annual cumulative CO<sub>2</sub> budget from  $-21 \text{ g C m}^{-2} \text{ yr}^{-1}$  to close to  $0 \text{ g C m}^{-2} \text{ yr}^{-1}$ . In contrast to the uptake events, the emission events showed no increased noise contamination compared to time periods without events.

Before calculating the CO<sub>2</sub> flux a correction needs to be applied for the influence of temperature and humidity on air density. For this purpose, the Webb, Pearman, and Leuning (WPL) correction (Webb et al., 1980; Text S5), in which the correction of both influence quantities is made as additive terms, is used by default. We investigated various possible sources of error in the measurement of the generally very low fluxes under





**Figure 4.** Frequency distributions for net longwave radiation (a), (c) and relative humidity (b), (d) classes during CO<sub>2</sub> emission (a), (b) and uptake (c), (d) events at the Bayelva site during the winter of 2015. The dashed lines in the histograms mark the median values. Ratio of noise-contaminated spectra of CO<sub>2</sub> concentration fluctuations to usable spectra, as obtained from the gas analyzer of the Bayelva eddy covariance system, as a function of (e) net longwave radiation, and (f) relative humidity classes, during the winter period.

Arctic conditions and found that during the strong CO<sub>2</sub> exchange events the WPL correction was responsible for the largest variation between the raw data and the final CO<sub>2</sub> flux estimates (see an example in Figure S9). The strong downward sensible heat fluxes during the events resulted in a large negative WPL correction term, which was up to 10 times larger than the uncorrected CO<sub>2</sub> fluxes (Figure S5c), leading to a potentially large error propagation from the sensible heat fluxes to the CO<sub>2</sub> fluxes. The uncertainty in the sensible heat flux determined by Foken et al. (2012) transforms into an uncertainty of between 0.2 and 1.2 μmol m<sup>-2</sup> s<sup>-1</sup> in our CO<sub>2</sub> fluxes, depending on the quality of the flux estimates. However, since the quality of the sensible heat fluxes during these events was generally good, this error propagation alone is unable to explain the anomalously high CO<sub>2</sub> flux measurements during the events. Furthermore, relying solely on error propagation from the sensible heat flux measurements to explain the CO<sub>2</sub> flux events would require large systematic underestimation of the sensible heat flux during emission events and overestimation of the sensible heat flux during uptake events.

### 3.4. Contribution of Physical Processes to the Event Fluxes

Since we did not identify any serious quality issues for the fluxes during the emission events, we then attempted to quantify the possible contributions of physical processes to the large flux values. We estimated the maximum amount of CO<sub>2</sub> that could be released from the snowpack for the emission event presented in Figure 3, using the measured snow properties (Text S4). Under the emission rate indicated by the flux values, the resulting amount of 0.10 g C m<sup>-2</sup> CO<sub>2</sub> that could potentially be released from the snowpack would have been used up only 3.5 h after the event started. Wind-induced pressure pumping would, therefore, only be able to account for about 20% of the total amount of CO<sub>2</sub> emitted during this event.

We also investigated the sensitivity of CO<sub>2</sub> emissions from the snowpack to changes in the snow density and in the CO<sub>2</sub> concentration in snow pores (Figure S10). Our estimates indicated that a CO<sub>2</sub> concentration in excess of 3,300 ppm would be required in the snow pores, together with a snow density of less than 80 kg m<sup>-3</sup>, in order for CO<sub>2</sub> emission similar to that indicated by the flux values to be possible. Such densities are typically only present in fresh snow, which had not been recorded for more than one month before the start of the event, meaning that even higher CO<sub>2</sub> concentrations would be required in the snow pores to explain the emission event. Furthermore, this particular event was preceded by another emission event that ended only one day before this one started, and it was followed by another event that started just four days after its conclusion. Each of these events featured a total CO<sub>2</sub> emission of approximately 0.4 g C m<sup>-2</sup> and was associated with high wind speeds, while between-event wind speeds were low. The short timespan between the individual events and the similarly large quantities of CO<sub>2</sub> emitted during each event would require a very rapid refilling of the CO<sub>2</sub> reservoir within the snowpack.

Wind-induced pressure pumping alone is, therefore, not able to account for the observed magnitude of the flux events since the relatively thin snow cover is unlikely to have been able to store enough CO<sub>2</sub>. Furthermore, the relatively long duration of the events compared to the short time spans between consecutive events makes it extremely unlikely that there would be a sufficient reservoir of CO<sub>2</sub> in the snowpack or in the air layer beneath the measurement instruments, which would be entirely used up during a single event and then need to be refilled before the next one.

#### 4. Discussion

Our results confirm that whether or not the data on winter high-flux CO<sub>2</sub> exchange events are included has important implications for the annual carbon balance at the high Arctic Bayelva site.

Using standard techniques for flux processing and quality filtering, we have shown that high CO<sub>2</sub> flux emission events at the Bayelva site during the winter of 2015 released a total of 16 g C m<sup>-2</sup> (over a period of 34.5 days) into the atmosphere, while uptake events contributed -22 g C m<sup>-2</sup> (over a period of 16.5 days) to the net annual CO<sub>2</sub> uptake of -21 g C m<sup>-2</sup> yr<sup>-1</sup>. Excluding the probably erroneous uptake events thus results in an annual CO<sub>2</sub> budget close to 0 g C m<sup>-2</sup> yr<sup>-1</sup>. In comparison, Lüers et al. (2014) identified a total contribution of only -5 g C m<sup>-2</sup> from uptake events and only 2 g C m<sup>-2</sup> from emission events to the annual CO<sub>2</sub> budget of 0 g C m<sup>-2</sup> yr<sup>-1</sup> at the Bayelva site in 2008/2009. However, these authors only considered one emission event and two uptake events, probably omitting smaller events that were not readily detectable by visual inspection. Most investigations have found that the Arctic tundra is a net annual sink for CO<sub>2</sub>. Consistent with the low productivity that would be expected from the sparsely vegetated Bayelva site (Lüers et al., 2014), its sink strength is at the lower end of the carbon uptakes documented from EC measurements across the Arctic (Corradi et al., 2005; Kutzbach et al., 2007; Lund et al., 2012; Soegaard & Nordstroem, 1999).

In accordance with Lüers et al. (2014), we found that the flux events were associated with changes in synoptic-scale forcing, involving high wind speeds and changes in air mass. While high wind speeds amplify fluxes of sensible and latent heat (Westermann et al., 2009), the positive correlation between wind speed and CO<sub>2</sub> fluxes was generally unexpected (although previously identified by Pirk et al., 2017), since soil respiration was assumed to be the dominant driver of CO<sub>2</sub> exchange during the Arctic winter. The reasons for this unexpected relationship probably differ between uptake events and emission events.

We suggest that uptake events are likely to be artefacts related to the limitations of conventional flux measurement and calculation techniques under the extreme Arctic winter conditions and should, therefore, be excluded from the time series. The positive correlation with wind speed is transferred from the sensible heat fluxes to the CO<sub>2</sub> fluxes via the WPL correction. Furthermore, the fluxes indicating a CO<sub>2</sub> uptake during the winter months are likely to be erroneous due to the limited ability of the gas analyzer to resolve very high frequency turbulent eddies. Our findings support the skepticism of Lüers et al. (2014) and Pirk et al. (2017) concerning the plausibility of abiotic physical explanations for winter CO<sub>2</sub> uptake, such as convective mixing of CO<sub>2</sub>-depleted air stored in the snowpack or CO<sub>2</sub> solution in meltwater.

For the emission events, the positive correlation between CO<sub>2</sub> fluxes and wind speed indicates a contribution from wind-driven abiotic processes. However, our estimates suggest that wind or pressure pumping alone would not be able to fully explain the high-flux events, contrary to the suggestion by Lüers et al. (2014). Nor were we able to identify any episodic upward transport of CO<sub>2</sub> at high wind speeds that had accumulated below the measurement height during calm periods, as previously identified for methane by Schaller et al. (2019). Assuming that the emission events are not an artefact of unidentified instrumental limitations, we suspect that advection of air masses from remote regions into the study area, as previously detected by trajectory and water vapor isotope analysis (Brandefelt & Holmén, 2001; Leroy-Dos Santos et al., 2020), contributes significantly to the large flux estimates. Episodic releases of CO<sub>2</sub> accumulated within the snowpack or below the measurement height would simply delay the detection of the emitted CO<sub>2</sub> by the instruments leaving the long-term carbon budget unaffected, while advection would introduce a bias to the local carbon balance (Aubinet et al., 2012).

Future research will need to (a) investigate the flux contributions from different physical mechanisms using additional experimental methods (e.g., profile and spatially distributed snow and atmospheric CO<sub>2</sub> concentration measurements, temperature profile measurements, regular snow depth and snow density measurements, and isotope analysis); (b) identify non-local low-frequency CO<sub>2</sub> flux contributions, for example, using different flux processing techniques; (c) consider the potential significance of error propagation from the energy fluxes to the CO<sub>2</sub> fluxes via the WPL correction, particularly at high wind speeds in low-flux environments (for example, through the simultaneous use of a closed-path gas analyzer, the data from which do not require a WPL correction); (d) investigate the interdependencies between the spectral resolution of a gas analyzer and net longwave radiation and humidity.

Deciphering winter CO<sub>2</sub> fluxes is particularly important in the North Atlantic sector of the Arctic, which is characterized by high (Isaksen et al., 2016; Wei et al., 2017; Zhang et al., 2004) and increasing (Rinke et al., 2017) levels of wintertime cyclonic activity. Taking the high levels of wintertime CO<sub>2</sub> exchange at face value can introduce a significant bias into long-term carbon budgets and thence into upscaled Arctic CO<sub>2</sub> exchanges, and ultimately into climate predictions.

## Data Availability Statement

All data are available in the manuscript, in the supporting information, or in data repositories. Meteorological and soil data are available from <https://doi.pangaea.de/10.1594/PANGAEA.880120>. The eddy flux data are openly available under CC-BY-4.0 in the FLUXNET data base (<http://www.europe-fluxdata.eu/>; ID:Sj-Blv).

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## Acknowledgments

The authors would first like to thank the AWIPEV station personnel for their support in maintaining the Bayelva site. The authors would also like to thank Christian Wille and Christoph Thomas for helpful discussions concerning the data processing. The authors are grateful to Archana Dayal for analyzing the CO<sub>2</sub> concentrations in the snowpack and to Niko Bornemann for field support during the winter 2016 season. The authors would also like to thank the two anonymous reviewers for their very helpful comments and suggestions which have enabled them to greatly improve their manuscript.



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