# Final author response to "Spatial variability of CO2 uptake in polygonal tundra – large overestimations by the conventional eddy covariance method"

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We thank the editor and reviewers for their ideas and suggestions to improve this paper. We have carefully considered them all and changed our manuscript accordingly. In the following we include a point-by-point response to the reviews (same as our replies to the referee comments), and attached a marked-up manuscript version showing the differences to the initially submitted version. Please note the changed title of the revised manuscript.

***Comment:*** *The authors measured net CO2 fluxes over polygonal tundra in the high arctic on Svalbard. They present an interesting and well written manuscript, but seem to interpret some aspects differently than this reviewer. I think it is important to exchange ideas and opinions between authors and reviewers and that it is positive to have new ideas presented even if not everyone agrees. However, my main points given below is that the language should reflect this in a somewhat clearer way so that the uninitiated reader does not misinterpret the universality of some statements.*
*Having said this, I must admit that I learned a lot reading this manuscript and fully support its publication after careful revisions.*
*Besides an important methodological aspect of how to compute defensible annual flux sums, a key statement of the paper is that all the detailed image analyses starting with pictures taken in 1948 cannot confirm a rapid degradation of this polygonal tundra, but rather support the view that this landscape has been quite stable over the last seven decades.*

**Reply:** We thank Professor Eugster for his thorough review of our manuscript and his helpful feedback. We carefully considered each of his comments, paying special attention to the potentially exaggerated universality of some of our statements.

***Main critique***

***Comment:*** *1. Your introduction completely misguided me in the wrong direction as your paper starts with the phrase "Carbon-rich Arctic tundra soils are often covered with polygonal ground patterns created by sub-surface ice wedges." – (1) Your paper is not addressing carbon-rich Arctic tundra soils! (2) Absence and presence of polygonal ground patterns is not directly related to carbon-richness of the soil (see e.g. Davis 2001). In fact, the non-orthogonal polygonal tundra patterns are mostly found on homogenous silty or sandy grounds, whereas the carbon-rich surfaces in my experience mostly show orthogonal polygonal patterns that differ from your site.*
*In fact, this all does not matter, it is simply a problematic first phrase (the one scientific writing is all about). Please rephrase and start your story in the direction where you actually go. In fact, only on page 12, line 8 my initial suspicion was resolved as you wrote "with its typically shallow organic horizon in the soil".*

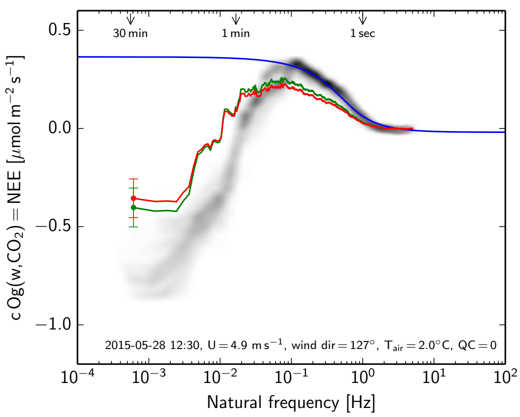
**Reply:** The top 100 cm of the soil in the EC footprint at the Adventdalen site contain about 30 kg SOC m-2 on average (personal communication with Peter Kuhry). In comparison with other permafrost-underlain well-developed soils, which can contain >100 kg SOC m-2 in the top 100 cm (see e.g. Hugelius et al. 2014), Adventdalen is not extremely carbon-rich. So we understand the confusion created by our first sentence and propose to resolve this misunderstanding by removing "carbon-rich" in the first sentence, so that it would read: "Arctic tundra is often covered with polygonal ground patterns created by sub-surface ice wedges."

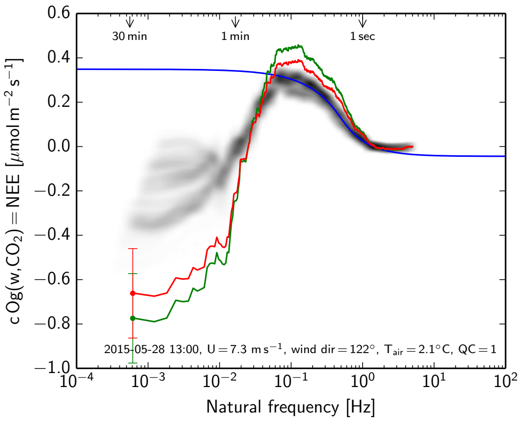
***Comment:*** *2. Abstract. I was confused by the your flux numbers. In principle, a negative sink is a source (page 1, line 8), but as an expert I guessed that you use the negative sign for net uptake and thus a sink of minus something is still a sink (not a source). OK, my recommendation is to put the number in parentheses to avoid the interpretation that it is a source. But the most confusing statement follows in the last line of the abstract: the text in lines 6 to 8 reads like: conventional calculation gives −46 gC m−2, improved ogive optimization gives −82 gC m−2 which is a strengthening of net uptake, but your text on line 14 calls this "a weakening of the CO2 sink" . . . I assume you wanted the reader to read the abstract differently. Please reword and clarify. Maybe also define your sign convention in the abstract.*

**Reply:** We acknowledge that these formulations could be misinterpreted and need clarification. So we propose to put these numbers in parentheses and define the sign convention at the first occurrence. The sentences 5 and 6 of the abstract would then read: "Non-local (low-frequency) flux contributions were especially pronounced during snowmelt and introduced a large bias of -46 gC m-2 to the annual CO2 budget in conventional methods (minus-sign indicating a higher uptake by the ecosystem). Our improved flux calculations with the ogive optimization method indicated that the site was a strong sink for CO2 in 2015 (-82 gC m-2) and due to differences in light-use efficiency, wetter areas with low-centered polygons sequestered 47% more CO2 than drier areas with flat-centered polygons."

***Comment:*** *3. You strongly vote for the ogive optimization method. I am not perfectly in agreement with your argumentation, though. As I mentioned initially, it is good to lead the discussion, but some more critical assessment of this method is required, which should be reflected in revised wordings at several places.*
*Your example in Fig. 2b clearly shows gravity waves seen with the bands of lenticular clouds. Under such conditions it is challenging to filter out the waves (which should not be considered fluxes). In principle, such conditions should fail any stationarity test and one could thus think of other methods to filter out such conditions.*

**Reply:** Firstly, the picture shown in Fig. 2b was not meant to represent the exact same 30-min period used in Fig. 2a, but only approximately the time of year during snowmelt. Using the time stamp of this photo, we now derived the matching EC ogives, which show the same features as the time period used in the original manuscript:






Admittedly, the data quality (QC) is worse and the ogive density map does indicate a degree of non-stationarity. So Prof. Eugster rightly points out that the period shown in Fig. 2b is not ideal for EC flux measurements with any method. However, this gravity wave event seemed to be rather short-lived because no lenticular clouds could be seen on photos taken 3 hours earlier:

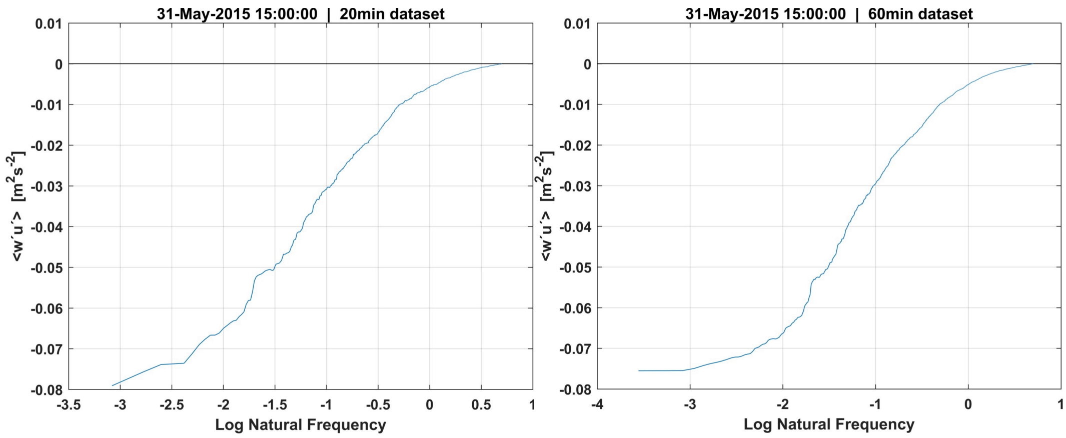

In fact, such lenticular clouds have otherwise never been observed during our site visits so the original picture shown in Fig. 2b is not very representative. To resolve this issue and minimize the potential for misunderstandings, we propose to exchange Fig. 2b in the revised manuscript with this picture, and indicate its time stamp in the figure caption (27 May 2015, 12:00 LT):

***Comment:*** *In the example given in Fig. 2a you basically truncate the turbulence cospectrum at 1/25 Hz, thus arguing that 25 seconds of measurements is enough to determine a half-hourly flux. This is in stark contrast to other concepts such as large eddy simulations where the generally accepted knowledge is used that it is the larger eddies—not the small ones—that are relevant for the turbulent fluxes between the surface and the atmosphere.*

**Reply:** The shortest dataset evaluated by the ogive optimization software is 10 min and the longest one is 60 min, thus covering a wider range of turbulence scales than conventional fixed-averaging methods. The example in Fig. 2a shows that all relevant flux contributions are carried by turbulence with a scale shorter than 25 sec. While that is interesting, we don't think it is particularly uncommon for EC measurements to have quite small flux contributions below this frequency. However, we definitely don't want to say that 25 sec are in general enough to determine a 30 min flux. To clarify this point, we propose to add the following sentence to the "Results" section describing Fig. 2a: "The ogive optimization model indicates that all relevant flux contributions are carried by turbulence with a scale shorter than about 25 sec in this example (which does, however, not mean that 25 sec are in general enough to determine a 30 min flux)."

***Comment:*** *Long ago I had to deal with a similar issue with my first measurements over lakes (Eugster et al. 2003) and there I used the direction of the momentum flux as a filter criterion. However, some software compute the momentum flux in a way that loses the directional sign so that it is unclear in which direction the momentum flux actually pointed. In principle the momentum flux (averaged over 30 minutes) should point towards the ground surface, but my experience is that in cases as you show in Fig. 2 there might be an upward momentum flux in the high frequencies which would question your interpretation that these high frequencies are better to estimate the local $CO_2$ flux. This only holds if your momentum flux in the high frequency range is clearly downwards. To accept your interpretation I would need to see the cospectrum or ogive of the horizontal windspeed time trace and the vertical windspeed time trace. The horizontal direction must be aligned with the flow so that $v' = 0$ and $u > 0$ ms−1. Otherwise, if the turbulent momentum flux is in the wrong direction then your argument that the corresponding $CO_2$ flux must be from the local surface would be incorrect.*
*Maybe you have also measured a wind profile? If the peak wind speed near the surface is below your eddy covariance (EC) measurement height, then this would be a condition where the momentum flux measured by EC is upwards, not towards the ground. I must admit that filtering with momentum flux direction is very rigorous and in many cases may be overly picky, but I hope I could explain you why I am not really of the same opinion as you (page 13, lines 12–18): if momentum flux is upwards, then your EC system sees the inversion interface between the cold air on the surface and the warm air aloft (which is present if you have clouds as those shown in Fig. 2), not the ground interface. You may overcome this with a more critical rewording; your text on lines 13–14 does not really provide a realistic "speculation".*

**Reply:** The ogive optimization software checks that the momentum flux is negative (towards the ground surface) in the mid-frequency range as one of the quality checks. While this test is described in the original publication of the method, we acknowledge that it would be relevant to briefly mention this test in the “Methods/Data processing” section of our manuscript. We therefore propose to add this sentence: “Ogive optimization furthermore only accepts periods with a negative momentum flux (i.e. directed toward the ground surface) in the mid-frequency range (10^-1.5 Hz).”
We don’t have vertical wind profile measurements, but we specifically checked the momentum flux ogives for the period given in Fig. 2a:




These ogives indicate a well-behaved and downwards-directed momentum flux, so we are confident that our arguments hold.
Regarding our speculation of a vertical $CO_2$ layering (page 13, line 13ff), we fail to see why it would be so unrealistic, and since it’s clearly indicated as a speculation we cannot really express it more carefully. Still, the possible stability layering suggested by Prof. Eugster could also be at work, so we propose to broaden this speculation a little bit to also mention possible layers of different atmospheric stability, so that the revised sentence would read: “One might speculate that the systematic occurrences of bi-directional fluxes are due to an atmospheric layering where low and high-frequency eddies circle through air masses with different atmospheric stability and $CO_2$ concentrations”

***Comment:*** *4. The limitations you list on page 2, lines 9–10 do not include the factor of self-heating if an open-path instrument is used. Later we see that you used a Licor 7200, but since your introduction is more general I recommend adding a statement here (many use open-path instruments in the Arctic due to power constraints). This is a factor that Baldocchi (2003) was not aware off, thus you should mention this after the citation.*

**Reply:** OK, we propose to add the following sentence here: “Also, when open-path gas analyzers are used, a bias may be introduced due to surface heating of the instrument itself (Burba et al., 2008).”

***Comment:*** *5. There is confusion about your argument why you focus on 2014/2015 data and less on 2013: on page 3, line 3 you write: “were only recorded as wet*

*molar densities and without the cell pressure necessary to convert them to dry mixing ratios". Is this a typo or did I misunderstand this statement? It is the H2O density measurement that is needed to convert from wet to dry mixing ratios. Temperature and cell pressure are only necessary to convert from densities to mixing ratios. A similar confusion is found on page 8, lines 1–2: "since they were wet rather than dry molar densities". Before you argued because of the mixing ratios, here one wonders why the ogive method should not work with wet molar densities if it would work with dry molar densities?*
*Please clarify these things. In principle you could use the Webb-Pearman-Leuning correction for your 2013 fluxes. Why did you not use this method to better profit from your interesting dataset?*

**Reply:** We acknowledge that these statements are somewhat inconsistent and misleading. The problem with the 2013 data is that a sample-by-sample conversion of recorded densities to mixing ratios would require the cell pressure, which hasn't been recorded. And while EddyPro can use the WPL correction to calculate corrected fluxes, this feature is not implemented in the current version of the ogive optimization software. We propose to clarify this issue in the "Methods/Data processing" section, writing: "We mainly focused on data collected between September 2014 and December 2015, when data quality and coverage was highest. CO2 concentrations collected in 2013 were only recorded as molar densities and without the cell pressure necessary for a sample-by-sample conversion to mixing ratios according to the Webb-Pearman-Leuning correction proposed by Sahlee et al. (2008), which is currently the only option implemented in the ogive optimization software. Hence, we only report 2013's fluxes from EddyPro as supplementary support for our findings."

The misleading sentence on page 3 line 23 would be removed. The sentence on page 8 lines 1-2 could then be simplified, reading:
"In 2013, EddyPro calculations yielded a smaller total annual CO2 balance of -79 gC m-2 (see Fig. S2d in the supporting information), whereas ogive optimization fluxes could not be calculated from 2013's raw CO2 measurements (cf. section 2.3)."

***<u>Detailed technical remarks</u>***

***Comment:*** *1/10: use K instead of ◦C for temperature differences*
**Reply:** OK

***Comment:*** *3/1: add "flux" in EC CO2 flux measurements*
**Reply:** OK

***Comment:*** *4/21: use "s" not "sec"*
**Reply:** OK, we changed this throughout the entire manuscript.

***Comment:*** *5/10: correlations between time series depend on the measurement interval; an r > 0.9 definitely does not hold for 10 Hz data, but may be seen with*

*monthly data. Either specify which aggregation level you talk about, or simply remove this statement in parentheses. Giving the distance is an objective information that should be sufficient.*
**Reply:** OK, we removed the statement in parentheses.

***Comment:*** *6/11–12: wording reflects some inconsistency in your statistical testing. I assume you used a t-test, but if you write "on average 10 cm larger thaw depth" then this implies a one-sided t-tests (testing for "greater than"). The wording on the line below ("this difference is not statistically significant") however is the wording for a two-sided test. Please rectify.*
**Reply:** OK, we propose to clarify that we used a two-sided t-test by changing this part to: "The thaw depth at the centers of the polygons around the EC tower was 66cm +/-9cm (mean +/-standard deviation, sample size N=30) by the end of August. Based on the polygons in the 50% EC footprint, the drier ESE fetch area featured a thaw depth of 69 cm +/-8 cm (N=4) while the wetter NW featured 79 cm +/-4 cm (N=4), which is not a statistically significant difference (p=0.10)."

***Comment:*** *7/9: do not specify "p < 10−12" since statistical models are not supposed to be accurate down to p < 10−12. Normally for low values it is sufficient to indicate something on the order of p < 0.0001 or so.*
**Reply:** OK

***Comment:*** *8/13: use K instead of ◦C for temperature differences*
**Reply:** OK

References:

Hugelius, Gustaf, et al. "Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps." Biogeosciences 11.23 (2014): 6573-6593.

Burba, George G., et al. "Addressing the influence of instrument surface heat exchange on the measurements of CO2 flux from open‐path gas analyzers." *Global Change Biology* 14.8 (2008): 1854-1876.

***Comment:*** *The manuscript of Pirk et al. presents interesting analyses of the spatial variability of topography and land-atmosphere fluxes of CO2 within a high-arctic polygonal tundra.*
*The small-scale spatial variability of topography was analyzed by photogrammetry of aerial photographs, which was used to produce a visual map and a digital elevation model. For an assessment of geomorphological changes of the polygonal tundra in the last decades, the new map was compared with historical aerial photographs. The study shows that no such geomorphological changes due to permafrost degradation could be detected at the high-arctic study site on Svalbard although the mean annual air temperatures on Svalbard have strongly increased in the last decades. This interesting result suggests a rather strong resilience of polygonal tundra to climate warming.*
*The small-scale spatial variability of land-atmosphere fluxes of CO2 was analyzed by separating the flux time series in periods with either wind directions from a drier landscape sector or in periods with wind directions from a wetter landscape sector, and separately analyzing the respective flux controls and flux balances for the two different sectors. The conclusion of this part of the study is also scientifically interesting and relevant as it indicates that drying of polygonal tundra, which might happen in many polygonal tundra areas due to permafrost degradation, will lead to a decrease of the CO2 sink capacity of these tundra landscapes.*
*Furthermore, the authors aimed at a better understanding of "how the spatial heterogeneity and larger-scale disturbances affect eddy covariance flux estimates by investigating the spectral composition of the eddy covariance signal". For this objective, they apply the ogive optimization method, which was only recently introduced by Sievers et al. (2015). Generally, I find the application of this new method and its comparison to the conventional eddy covariance method presented by this manuscript highly valuable and of great relevance for the eddy covariance flux community. However, I think that the study does not provide enough evidence and deep-enough discussion to substantiate their claim that the ogive optimization method produces more trustworthy results than the conventional method. I discuss this in more depth in the list of specific comments below.*
*The language of the manuscript is clear and easy to follow. The figures are of high quality.*
*I recommend the manuscript of Pirk et al. for publication in Biogeosciences after major revisions considering my comments above and below.*

**Reply:** We thank Prof. Lars Kutzbach for his thorough review and his comments to further improve our manuscript.

***Specific comments:***

***Comment:*** *(1) Page 1: Title: I suggest weakening the rather strong and general statement in the second part of the title: "large overestimations by the conventional eddy covariance method". I think that it is not clear enough at this point, which of the two methods – the conventional or the ogive optimization – delivers more trustworthy results. It is definitely an important finding of this study that the two methods lead to such strongly deviating results, but for a decision which method* *should be preferred, a better understanding of the atmospheric flow or experimental set-up effects potentially causing these biases would be needed. Furthermore, if the title suggests that the main message of the article is that the conventional eddy covariance method overestimates the CO2 uptake, the existing theoretical knowledge about eddy covariance measurements over heterogeneous landscapes and complex terrain must be more extensively reflected both in the introduction and the discussion. If the main message of the article is on the biases of the eddy covariance method, it is not enough to just refer to the work of Sievers et al. (2015). Then, the authors have to discuss their findings in the light of the extensive work on eddy covariance measurements over heterogeneous landscapes and in complex terrain (e.g., Mahrt et al. (1994), Finnigan et al. (2003), Inagaki et al. (2006), Aubinet et al. (2010), and others) in the current manuscript.*

**Reply:** OK, we propose to weaken the statement in the second part of the title to take some weight off the eddy covariance calculations. So the revised title would be: "Spatial variability of CO2 uptake in polygonal tundra – assessing low-frequency disturbances in eddy covariance flux estimates"

We furthermore propose to extend the introduction including the mentioned literature by adding the sentences: "Large-scale surface heterogeneity has been observed and simulated to induce thermal circulations on the mesoscale that can impede the turbulent flux estimation (Mahrt et al., 1994; Inagaki et al., 2006), while complex terrain may lead to horizontal advection of gases and thereby biased flux estimations (Finnigan et al., 2003; Aubinet et al., 2010). Finnigan et al. (2003) showed that the averaging operation and coordinate rotation commonly applied in EC flux calculations can lead to co-spectral distortions and a loss of flux."

In our discussion, we propose to make specific mention of the CO2 co-spectra given in Figures 15 and 16 of Finnigan et al. (2003), which show an indication of a similar frequency mismatch below 10^-3 Hz:

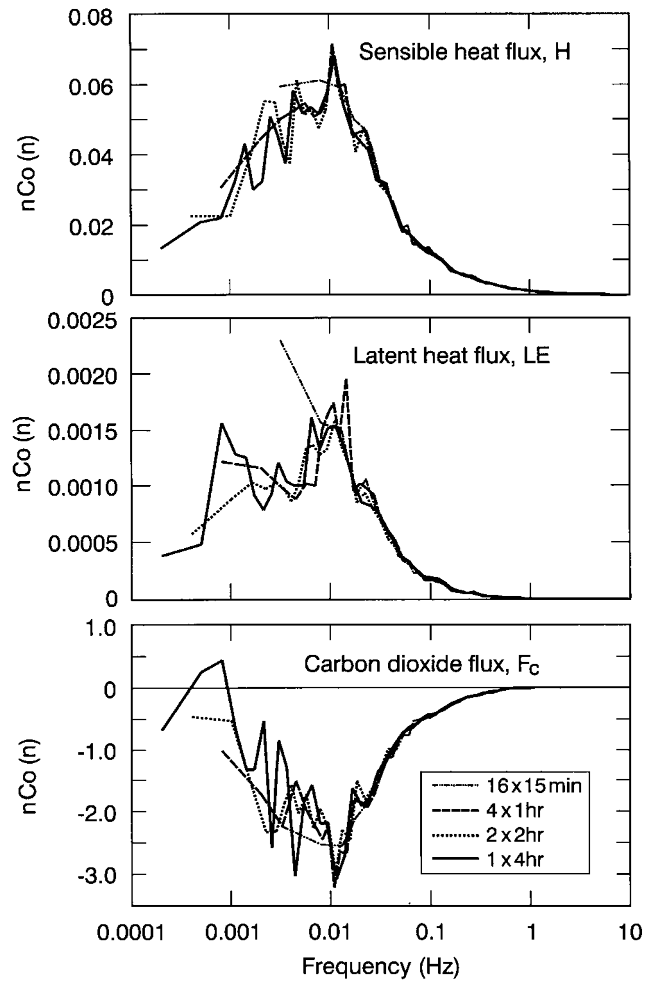



*Figure 15.* Ensemble averaged scalar cospectra for the period 0800–1200 EST from 9 days of Tumbarumba data. The cospectra are plotted in area preserving form. Each plot consists of four curves corresponding to averaging and rotation periods of 15 min, 1 h, 2 h and 4 h. The curves extend to successively lower frequency as the averaging period increases. (a) Sensible heat, H. (b) Latent heat, *LE* from the closed-path Licor instrument. No high frequency correction has been applied. (c) Carbon dioxide flux, $F_C$ from the closed-path Licor instrument. No high frequency correction has been applied.

The fact that the low frequency shift is here only observed for CO2 may have something to do with the low covariance of CO2 observations, relative to sensible and latent heat fluxes.

***Comment:*** *(2) Page 2, lines 21-22: The paper of Kutzbach et al. (2007) reports an annual net ecosystem CO2 exchange (NEE) of −71 g CO2 m−2, which equals to about 19 g C m-2, for polygonal tundra (Kutzbach et al., 2007). Please correct this.*

**Reply:** OK, we corrected this.

***Comment:*** *(3) Page 3, lines 7-9: I think that it would be important to more thoroughly describe and discuss the patterns of prevailing wind directions and the microclimatic situation in general. The investigation site is located in a valley surrounded by rather high mountains, and it is near to the sea (fjord). Therefore,* *sea and land breezes, katabatic or anabatic winds as well as gravity waves may have important effects on the air movements analyzed by the eddy covariance system. This could be relevant for the discussion of the observed frequency mismatches in the co-spectra and ogives, respectively.*

**Reply:** OK, we propose to extend the site description with the following sentences: "The surrounding mountains feature plateaus of around 450 m a.s.l., as well as peaks and ridges of up to 1000 m a.s.l, which are still partly glaciated. Wind directions are generally oriented along the valley, with dominating easterlies in wintertime (coming from inland Spitsbergen), and an approximately even distribution of easterlies and westerlies in summertime (westerlies coming from the fjord). Long-term statistics indicate that wind speeds in Adventdalen are below 5 m s-1 for about 70% of the year (and below 10 m s-1 for about 97%), with a most frequent wind speed of about 3 m s-1."

***Comment:*** *(4) Page 3, lines 12-14: Please give here more information on the soil properties in this polygonal tundra. In particular, organic carbon contents in the different soils of polygonal tundra would be of interest. Spatial variability of soil organic matter contents is likely pronounced in the polygonal tundra (Zubrzycki et al., 2013).*

**Reply:** OK, we propose to also extend this part of the site description with what has been reported by other studies: "The measurement site is located on a river terrace on the flat part of a large alluvial fan, where the ground is patterned by ice-wedge polygons. These coarse alluvial deposits are covered with a few ten centimeters of organic material and fine-grained eolian deposits (loess), which typically stem from wind erosion in the braided riverbed when it dries out in autumn (Bryant et al. (1982), Oliva et al. (2014)). The site's soil organic carbon content in the uppermost 100 cm soil is about 30 kgC m-2 (personal communication with Peter Kuhry)."

***Comment:*** *(5) Page 3, lines 14-16: Please give more detailed information about the vegetation composition within the polygonal tundra. How does vegetation differ between low- center polygons of different degradation/drainage conditions? Please give information on (approximate) ground coverages of shrubs, sedges and mosses at polygon rims and polygon centers of different water levels. The coverage of mosses is of high interest since they can start photosynthesizing directly after snowmelt (or even earlier) (Oechel , 1976, Tieszen et al., 1980). When discussion the early CO2 sink function suggested by the conventional eddy covariance method, coverage of mosses is of interest.*

**Reply:** Due to the patterned microtopography, there is considerable variability in the vegetation cover. A dedicated vegetation analysis has not been conducted, so we can unfortunately not estimate the overall moss cover. Our general assessment is that the three vegetation layers (shrubs, sedges, mosses) clearly overlap in most areas. Drier areas are dominated by shrubs and sedges, while wetter areas are dominated by sedges and mosses. So we can assume sufficient

moss coverage for the discussion of the early onset of net CO2 uptake indicated by the conventional method (details given in reply to comment 8 below).
To give some more information about the specifically relevant moss cover, we propose to add these sentences to the site description: “The moss cover is sparse in drier polygons where shrubs dominate the vegetation community, while the wetter areas at local depressions feature an almost continuous moss cover. Within individual polygons the moss coverage typically increases from the drier rim to the wetter center.”

***Comment:*** *(6) Page 3, line 23: This sentence is confusing. You need the pressure and temperature inside the cell to convert from molar densities to mixing ratios. You need water vapor measurements to convert from mole fractions (referred to wet air) to mixing ratios referred to dry air. Please write this in a clearer way.*

**Reply:** We acknowledge that this sentence needs clarification (as also pointed out in comment 5 by reviewer #1). We propose to change it to: “CO2 concentrations collected in 2013 were only recorded as molar densities and without the cell pressure necessary for a sample-by-sample conversion to mixing ratios according to the Webb-Pearman-Leuning correction proposed by Sahlee et al. (2008), which is currently the only option implemented in the ogive optimization software. Hence, we only report 2013's fluxes from EddyPro as supplementary support for our findings”

***Comment:*** *(7) Page 6, lines 4ff: How did the footprint extents differ before, during and after snowmelt? The snow cover could have a significant effect on footprint extents due to its lower roughness length. Could this affect the flux co-spectra during snowmelt?*

**Reply:** In our footprint estimation we kept the roughness length constant at 1 cm throughout the year. This value might be slightly too high for snow (which is typically assigned 0.5 cm) and maybe slightly too low for open tundra vegetation (typically assigned 3 cm). We have however not undertaken dedicated efforts to quantify this parameter more precisely. Therefore, we might overestimate the footprint extent a little bit during the snow-free season, and underestimate it a little during snow-covered conditions.
The surface roughness could indeed affect the flux co-spectra -- in principle at any time of year. One conceivable mechanism is that a greater roughness length could break down larger turbulence into smaller turbulence, thus shifting some of the co-spectrum toward higher frequencies. We propose to add this consideration to our discussion, stating: “Snowmelt also entails a change in the typical surface roughness length, which is slightly smaller for snow than open tundra vegetation. A greater roughness could break down larger turbulence into smaller turbulence, thus shifting some of the flux co-spectrum toward higher frequencies. However, such spectral shifts would be no problem for the functionality of the used flux calculation schemes and cannot readily explain bi-directional fluxes even if the surface roughness is spatially heterogeneous.”

***Comment:*** *(8) Page 6, lines 13ff: When considering the pronounced spatial variability within the footprints of the eddy covariance measurements, I wonder how much you can be sure that the frequency mismatches are due to local and non-local flux contributions. Could this mismatch also be caused by flux heterogeneity within the (local) footprint? The position of the flux tower appears to be at a drier patch compared to the surroundings in the studied polygonal tundra. When moving from the tower in both main prevailing wind directions, the first wet polygons are found some 30 m to 50 m away from the tower. Could it be possible that the observed frequency mismatches (commonly sign of covariance different for eddies larger than about 30 m than for eddies smaller than 30 m) are due to positive CO2 fluxes from the drier polygons near the tower (reflected better in the high frequencies) and negative CO2 fluxes at the wetter tundra at larger distance from the tower (reflected in the low frequencies)? If wetter tundra has more mosses, this could lead to earlier negative fluxes than at drier sites with less mosses since mosses can start photosynthesizing directly after snowmelt (or even earlier) (Oechel , 1976, Tieszen et al., 1980). Since the strongest frequency mismatches were observed during the snowmelt period, it would be also very interesting to have more information on the snow distribution: Was there the same snow coverage near the flux tower in the drier polygons than further away (30-50 m) in the wetter polygons?*

**Reply:** When we first noticed the systematic frequency mismatches during snowmelt we were thinking along exactly the same lines as Prof. Kutzbach describes here, namely that different frequencies represent different areas, of which some are CO2 sources and others CO2 sinks. However, due to the comparably large scale at which is mismatch occurs (around 25 sec, corresponding to more than 30 meter), we largely discarded this explanation again. We don't have a detailed vegetation map or a good estimation of the snow coverage throughout the snowmelt period, but we generally estimate the patchiness during snowmelt to be smaller than the size of the eddies corresponding to the lower frequencies.
Moreover, we observed the frequency mismatches from both wind directions, and since there are likely less mosses in the east than the west, the moss mechanism for this mismatch becomes even less likely.
However, we cannot fully exclude the mechanism outlined by Prof. Kutzbach, so we propose to add the following sentences to our discussion: "However, we cannot fully exclude that the frequency mismatches are caused by flux heterogeneity within the local footprint. It could be possible that the drier areas near the EC tower (reflected better in the high frequencies) are net CO2 sources, while wetter areas at larger distances from the tower (reflected in the low frequencies) are net CO2 sinks. A heterogeneous vegetation composition might cause such flux heterogeneity during snowmelt, because unlike shrubs and sedges, mosses have photosynthetically active tissue that may overwinter so that they can start photosynthesizing at low rates already during snowmelt (Oechel et al. (1976), Tieszen et al. (1980)). While some degree flux heterogeneity is certainly present at any time of year, its effect might be too small to explain the large frequency mismatches observed particularly during snowmelt. Nevertheless, our observations might incentivize future studies to investigate the frequency dependency of EC footprints."

***Comment:*** *(9) Page 6, line 30: What do you mean with "better performance"? How did you assess "performance"? I think that CO2 uptake during the snowmelt period (as it is illustrated in in Figure 2b) would not be as implausible as suggested by the authors since mosses can start photosynthesizing directly after snowmelt (or even earlier, see above).*

**Reply:** We acknowledge that "better performance" is not the best formulation here and propose to change this sentence to: "Since the frequency mismatches cannot be resolved in conventional calculations, we focus on the NEE fluxes calculated by the ogive optimization method for the ecosystem characterization."

***Comment:*** *(10) Page 7, line 6: What is exactly meant by "combined footprint"? Just using the original eddy covariance flux time series without separating periods of different wind directions? Or have you applied some sort of spatial weighing of the contributions of wetter and drier polygonal tundra to the whole are of interest? If you do the former, then the CO2 balances for the "combined footprint" would depend to a large degree on the frequency distribution of wind directions.*

**Reply:** Yes, we simply mean using all fluxes without separating wind directions, and we agree that the derived balances will depend on the occurrence of the two wind directions. We still chose to report these CO2 balances because this seems to be quite common for EC studies. To clarify the meaning of "combined footprint" in this case, we propose to change this sentence to: "The annual balance of the combined footprint (using all fluxes without separating periods of different wind directions) was -82 gC m-2 in 2015."

***Comment:*** *(11) Page 7, lines 9-10; Page 8, lines 1-2: It does not become clear why you can calculate eddy covariance fluxes without having mixing ratios referred to dry air by using the conventional EddyPro method but not by using the ogive optimization method. Couldn't you apply the classic WPL approach (Webb et al. (1980) as refined by Ibrom et al. (2007)) to fluxes calculated by both methods?*

**Reply:** We acknowledge that our formulations of this issue weren't clear enough (as also noted by reviewer #1). While it is in principle possible to use the WPL approach in ogive optimization, it is not implemented in the current version of this software. So this task remains to be solved in future studies.
We propose to clarify this part of the text, as noted in our reply to comment 5 of reviewer #1.

***Comment:*** *(12) Page 12, lines 7-8: The observed annual CO2 uptake appears indeed very large. However, I think that such an uptake is well possible. For example, high CO2 uptake was also observed at coastal wet sedge tundra near Barrow, Alaska, by Harazono et al. (2003).*

**Reply:** We thank the reviewer for pointing us toward this publication by Harazono et al. This paper only reports budgets from spring to autumn, i.e. not the full annual $CO_2$ budget including possible wintertime release of $CO_2$. Still, we propose to mention this large growing season uptake in our discussion by adding the following sentence: "The summertime $CO_2$ sink of Adventdalen is comparable to that of a coastal wet sedge tundra ecosystem at Barrow, Alaska (-105 to -162 gC $m^{-2}$) (Harazono et al. (2003))."

# Spatial variability of $CO_2$ uptake in polygonal tundra – assessing low-frequency disturbances in eddy covariance flux estimates

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**Abstract.** The large spatial variability in Arctic tundra complicates the representative assessment of $CO_2$ budgets. Accurate measurements of these heterogeneous landscapes are, however, essential to understand their vulnerability to climate change. We surveyed a polygonal tundra lowland on Svalbard with a UAV, mapping ice-wedge morphology to complement eddy covariance (EC) flux measurements of $CO_2$. The analysis of spectral distributions showed that conventional EC methods do not accurately capture the turbulent $CO_2$ exchange with the spatially heterogeneous surface which typically features small flux magnitudes. Non-local (~~low frequency~~low-frequency) flux contributions were especially pronounced during snowmelt and introduced a ~~bias to the annual $CO_2$ budget~~ large bias of $-46$ gC m$^{-2}$ to the annual $CO_2$ budget in conventional methods (minus-sign indicates a higher uptake by the ecosystem). Our improved flux calculations with the ogive optimization method indicated that the site was a strong sink for $CO_2$ ~~of~~ in 2015 ($-82$ gC m$^{-2}$~~in 2015~~) and due to differences in light-use efficiency, wetter areas with low-centered polygons sequestered 47% more $CO_2$ than drier areas with flat-centered polygons. While Svalbard has experienced a strong increase in mean annual air temperature of more than 2~~°C~~ K in the last few decades, historical aerial photographs from the site indicated stable ice-wedge morphology over the last seven decades. Apparently, warming has thus far not been sufficient to initiate strong ice-wedge degradation, possibly due to the absence of extreme heat episodes in the maritime climate on Svalbard. However, in Arctic regions where ice-wedge degradation has already initiated the associated drying of landscapes, our results suggest a weakening of the $CO_2$ sink of polygonal tundra.

## 1 Introduction

~~Carbon-rich Arctic tundra soils are~~ Arctic tundra is often covered with polygonal ground patterns created by sub-surface ice wedges (*Leffingwell*, 1915; *Mackay*, 1974; *Romanovskii*, 1985; *Minke et al.*, 2007). While ice wedges need centuries or millennia to form through the infiltration and refreezing of meltwater in thermal contraction cracks, they have been reported to degrade rapidly during the last decades with permafrost warming, which significantly alters soil drainage and moisture (*Fortier* *et al.*, 2007; *Liljedahl et al.*, 2016). Especially in the high Arctic where permafrost warming occurs fastest (*Romanovsky et al.*, 2010), these hydrological changes can influence the land-atmosphere exchange of greenhouse gases such as carbon dioxide ($CO_2$), which could affect the long-term carbon sink function of these ecosystems (*Schuur et al.*, 2015; *Jorgenson et al.*, 2015).

~~$CO_2$~~ Carbon dioxide fluxes in polygonal tundra are characterized by large spatial variability, which complicates their accurate assessment over larger areas (*McGuire et al.*, 2012). On a scale of hectares to $km^2$, the micro-meteorological eddy covariance (EC) technique has become widely used to measure the net ecosystem exchange of $CO_2$ (NEE), because it provides a good compromise between directness of measurement, ecosystem disturbance, and technical reliability. The EC technique estimates NEE integrated over a footprint area upwind based on point measurements of the covariance of vertical wind speed and $CO_2$ concentration (*Aubinet et al.*, 2012). Careful calculations have been found to provide defensible estimates of the true $CO_2$ flux, with the main systematic uncertainties stemming from non-steady atmospheric conditions, heterogeneous surfaces and complex terrain (*Baldocchi*, 2003). Large-scale surface heterogeneity has been observed and simulated to induce thermal circulations on the mesoscale that can impede the turbulent flux estimation (*Mahrt et al.*, 1994; *Inagaki et al.*, 2006), while complex terrain may lead to horizontal advection of gases and thereby biased flux estimations (*Finnigan et al.*, 2003; *Aubinet et al.*, 2010). *Finnigan et al.* (2003) showed that the averaging operation and coordinate rotation commonly applied in EC flux calculations can lead to co-spectral distortions and a loss of flux. Also, when open-path gas analyzers are used, a bias may be introduced due to surface heating of the instrument itself (*Burba et al.*, 2008). Results from different conventionally used software packages for EC calculations have been shown to agree in temperate grasslands and forests (*Fratini and Mauder*, 2014), but the typically low flux magnitudes in high Arctic environments pose considerable challenges for the correct estimation of EC fluxes (*Sievers et al.*, 2015a). Special care must be taken during the long cold season, when small $CO_2$ releases can sum up to a significant portion of the total annual carbon budget (*Fahnestock et al.*, 1999; *Björkman et al.*, 2010; *Lüers et al.*, 2014).

Across the Arctic tundra, previous studies have shown differing $CO_2$ budgets depending on the characteristics of the landscape. EC $CO_2$ measurements from a well studied high Arctic tundra site in Northeast Greenland indicate a considerable annual carbon sink ($-64$ gC $m^{-2}$) in a wet fen (*Soegaard and Nordstroem*, 1999), while the neighboring dry heath constitutes a weaker sink on average ($-21$ gC $m^{-2}$) (*Lund et al.*, 2012). Measurements from Alaskan tussock tundra show that non-growing season releases of $CO_2$ can also exceed the growing season uptake rendering the ecosystem a small net annual source ($+14$ gC $m^{-2}$) (*Oechel et al.*, 2014). A wet tussock grassland in NE Siberia was found to be a moderate annual sink ($-38$ gC $m^{-2}$) (*Corradi et al.*, 2005), while wet polygonal tundra in the Lena River Delta was estimated to be a ~~substantial~~ weaker annual $CO_2$ sink ($-$~~71~~19 gC $m^{-2}$) (*Kutzbach et al.*, 2007). Some of these studies rely on modeled fluxes to fill large data gaps during wintertime, which increases the uncertainty of the annual sums.

As opposed to other permafrost-underlain regions where soils could become wetter in the future (*Natali et al.*, 2011; *Johansson et al.*, 2013), polygonal tundra is predicted to dry upon permafrost degradation (*Liljedahl et al.*, 2016): the ground above melting ice wedges subsides, which interconnects the polygon troughs and creates an effective drainage network for the wet polygon centers (*Fortier et al.*, 2007). This simultaneous wetting of polygon troughs and drying of polygon centers is a signature that can be detected in time series of historical aerial photographs to provide large-scale evidence of the process (*Necsoiu et al.*, 2013). *Liljedahl et al.* (2016) described such ice-wedge degradation as a widespread Arctic phenomenon, which changed surface drainage patterns in less than one decade. To study the progressive change in plant communities and biogeochemistry following such a disturbance space-for-time substitutions have proven to be a powerful tool (*Rastetter*, 1996). The associated hydrological changes have thus been linked to significant changes in ~~methane~~ carbon fluxes in Alaskan polygonal tundra ~~(*Vaughn et al.*, 2016)~~during the growing season (*Lara et al.*, 2015; *Vaughn et al.*, 2016), but their ~~larger scale~~ year-round effect on an ecosystem's $CO_2$ budget is yet to be quantified.

Such an assessment could be improved by high-resolution topographical surveys using unmanned aerial vehicles (UAVs). Apart from the visual picture UAVs provide, the series of photographs from multiple angles allows the reconstruction of the 3D geometry of the surface (*Ullman*, 1979; *Westoby et al.*, 2012), which can give valuable insights into the drainage patterns. In the present study, we explore the potential of this technique in combination with EC $CO_2$ flux measurements in polygonal tundra on Svalbard to characterize the spatial heterogeneity of the ecosystem. We aim to understand how the spatial heterogeneity and larger-scale disturbances affect EC flux estimates by investigating the spectral composition of the EC signal. We further relate the spatial differences in NEE to the observed historical, and the predicted future evolution of ice-wedge polygons.

## 2 Materials and Methods

### 2.1 Site description

The field site is located ~~on a river terrace~~ at the bottom of a large, ~~U-shaped~~permafrost-underlain, glacial valley called Adventdalen on Spitsbergen, Svalbard, approximately 6 km from a fjord (78°11′N, 15°55′E). The surrounding mountains feature plateaus of around 450 m a.s.l., as well as peaks and ridges of up to 1000 m a.s.l, which are still partly glaciated (*De Haas et al.*, 2015). Wind directions are generally oriented along the valley, with dominating easterlies in wintertime (coming from inland Spitsbergen), and an approximately even distribution of easterlies and westerlies in summertime (westerlies coming from the fjord). Long-term statistics indicate that wind speeds in Adventdalen are below 5 m $s^{-1}$ for about 70% of the year (and below 10 m $s^{-1}$ for about 97%), with a most frequent wind speed of about 3 m $s^{-1}$. The mean annual air temperature at the closest weather station (Svalbard airport, approximately 10 km away) was −6.7°C between 1961 and 1990 (*Førland et al.*, 2012), which has increased to −3.75°C in the period between 2000 and 2011 (*Christiansen et al.*, 2013). The total annual precipitation is about 190 mm, of which about half falls as snow (*Førland et al.*, 2012). The ~~landscape setting in combination with these climatic conditions created a continuous permafrost fen, in which~~ measurement site is located on a river terrace on the flat part of a large alluvial fan, where the ground is patterned by ~~low-centered~~ ice-wedge polygons (*Christiansen*, 2005; *Harris et al.*, 2009). ~~The~~ These coarse alluvial deposits are covered with a few ten centimeters of organic material and fine-grained eolian deposits (loess), which typically stem from wind erosion in the braided riverbed when it dries out in autumn (*Bryant*, 1982; *Oliva et al.*, 2014). The site's soil organic carbon content in the uppermost 100 cm soil is about 30 kgC $m^{-2}$ (personal communication with Peter Kuhry). The vegetation at the Adventdalen site features *Salix polaris* in drier areas, *Eriophorum scheuchzeri* and *Carex subspathacea* in wetter locations~~, and moss species in usually inundated spots.~~. The moss cover is sparse in drier polygons where shrubs dominate the vegetation community, while the wetter areas at local depressions feature an almost continuous moss cover. Within individual polygons the moss coverage typically increases from the drier rim to the wetter center.

### 2.2 Measurement setup

The EC setup consisted of a top-mounted ultra-sonic anemometer (USA-1, Metek GmbH, Germany) and an infra-red gas analyzer (Li-7200, Li-Cor Inc., USA), both of which were sampling and recording data at a rate of 10 Hz. The measurement height was 2.8 m above ground level. From there the gas was pumped to the Li-7200 at a flow rate of 15 L min$^{-1}$ via a 1 m long, insulated intake tube supplied by the manufacturer.

~~We mainly focused on data collected between September 2014 and December 2015, when data quality and coverage was highest. $CO_2$ concentrations collected in 2013 were only recorded as wet molar densities and without the cell pressure necessary to convert them to dry mixing ratios. We therefore consider 2013's fluxes less certain and only use them as supplementary support for our findings.~~

Ancillary meteorological measurements (e.g. solar radiation, snow and soil temperatures) were collected on and around the same tower, sampled every 10 ~~sec~~ s and averaged to 30 min values. Due to the relatively remote location without line power, the system was supplied by lead-acid batteries, which were charged by a wind generator (350 W peak output) and solar panels (275 W peak output), as well as a fuel cell in summertime (90 W).

Complementary to the EC setup, we measured NEE in the EC footprint with a set of five transparent, automatically operated, flux chambers using the closed chamber technique. These chambers were connected to a gas analyzer (SBA-4, PP Systems, UK), which measured $CO_2$ concentrations at a rate of 0.625 Hz. Flux estimates were derived from exponential least-squares regression of the 5 min closure time of the concentration time series (details of this measurement system and flux estimation procedure are provided in *Pirk et al.* (2016b) and references therein).

To assess differences in the active layer depth, thaw depths were probed at the centers of 30 polygons in the EC footprint at the end of August 2016.

### 2.3 Data processing

EC flux estimates were derived using the recently proposed ogive optimization method (version 1.0.5, toolbox publicly available through the Mathworks file exchange) (*Sievers et al.*, 2015b). In this context, ogives are cumulative co-spectra of vertical wind speed (w) and $CO_2$ concentration (denoted Og(w,$CO_2$)), i.e. a spectral decomposition of the EC flux estimate. The method optimizes a spectral distribution model (*Desjardins et al.*, 1989; *Lee et al.*, 2006; *Foken et al.*, 2006) to a density map of 14 000 ogives obtained by varying the dataset length and de-trending interval. The key to this method is the assumption of a dynamic spectral gap between often overlapping spectral flux contributions (*Sievers et al.*, 2015b). This approach effectively separates the turbulent flux from contributions of larger-scale motions (mesoscale atmospheric movements), which can give non-local flux contributions at low frequencies (*Aubinet et al.*, 2012; *Sievers et al.*, 2015b).

To further investigate the effect of ~~low frequency~~ low-frequency contributions we compared ogive optimization to the widely used EddyPro software package (Li-Cor Inc., version 6.1.0), following the conventional assumption about the presence of a fixed spectral gap corresponding to the 30 min flux averaging interval. We used simple linear de-trending, and applied spectral corrections according to *Moncrieff et al.* (1997, 2004) (EddyPro default).

Both EddyPro and ogive optimization perform basic quality control and pre-processing of the 10 Hz raw data following *Vickers and Mahrt* (1997) (e.g. gap detection, spike removal, signal alignment, anemometer tilt correction). Unacceptable raw data were not processed further. To ensure sufficient turbulent mixing near the surface, we also filtered out data points with a friction velocity smaller than 0.1 m secs$^{-1}$ for both methods. Ogive optimization furthermore only accepts periods with a negative momentum flux (i.e. directed toward the ground surface) in the mid-frequency range ($10^{-1.5}$ Hz). Following *Foken and Wichura* (1996), EddyPro fluxes were additionally filtered for non-steady wind conditions (discarding fluxes with quality flag 2). Calculated ogive optimization fluxes, on the other hand, were only discarded if the modeled ogive spectral distribution could not describe the data sufficiently well. These filters, in addition to down-time caused by technical problems, led to an overall data coverage with valid fluxes of 45% in 2015 for the ogive optimization and 35% with EddyPro. A large number of these flux calculations have been visually inspected to ensure that the methods performed as expected. In this analysis, we noticed that the automatically determined time lags between w and $CO_2$ concentration varied unrealistically, which introduced noise to the fluxes—especially at low magnitudes. We therefore used a constant value of 0.3 sec s (i.e. the typically expected time lag given our setup) for the flux calculation with both methods.

We mainly focused on data collected between September 2014 and December 2015, when data quality and coverage was highest. Carbon dioxide concentrations collected in 2013 were only recorded as molar densities and without the cell pressure necessary for a sample-by-sample conversion to mixing ratios according to the Webb-Pearman-Leuning correction proposed by *Sahlée et al.* (2008), which is currently the only option implemented in the ogive optimization software. Hence, we only report 2013's fluxes from EddyPro as supplementary support for our findings.

Subsequently, the calculated NEE was used to determine the ecosystem's light response characteristics during the snow-free period (beginning of June until end of September). One way to parameterize the relationship between NEE and incoming photosynthetically active radiation (PAR) is the Misterlich function,

$$\mathrm{NEE} = -\left(F_{\mathrm{csat}} + R_{\mathrm{d}}\right)\left(1 - \exp\left(-\frac{\alpha\,\mathrm{PAR}}{F_{\mathrm{csat}} + R_{\mathrm{d}}}\right)\right) + R_{\mathrm{d}}, \tag{1}$$

where the three parameters $F_{\mathrm{csat}}$, $R_{\mathrm{d}}$, and $\alpha$ correspond to the flux at light saturation, dark respiration, and light-use efficiency, respectively (e.g., *Falge et al.*, 2001). Such light response curves can yield further insights to the underlying drivers of NEE. These parameters were derived from least-squares regressions of measured NEE and PAR (derived from short wave incoming radiation) in a rolling time window of 10 days, which was successively increased by 1 day if less than 100 valid NEE-PAR measurements were available (following *Lund et al.* (2012)).

For cumulative flux calculations and annual sums we employed the gap-filling algorithm proposed by *Reichstein et al.* (2005), which operates on the basis of mean diurnal variations of temperature, incoming short wave radiation, and vapor pressure deficit as drivers for NEE. As some of the gaps in our NEE measurements were caused by power outages (when the entire measurement system shut down), the ancillary data for gap-filling were taken from the New Adventdalen Weather Station (run by the University Centre in Svalbard) with a distance of about 2.5 km from our site(typical meteorological data

~~correlations r>0.9)~~. This procedure yielded the best gap-filling quality (class A) in 96% of the flux estimates that had to be gap-filled in 2015. Still, gaps in NEE measurements can be assumed to dominate the total random error of the annual sums (*Aurela et al.*, 2002). To quantify this uncertainty, we tested the sensitivity of the annual sums to artificially added gaps in the NEE time series. Since the uncertainty introduced by a gap depends on its length and time of year, we repeated the gap-filling on 300 different time series obtained by adding single gaps with a length between 1 and 23 days (i.e. 2 days longer than our longest gap) which were equally distributed over the year (starting every 15 days). The resulting distribution of annual sums was used to assess the result's random error.

The EC footprint estimation was performed according to *Kljun et al.* (2015), using a fixed zero-plane displacement of 10 cm, and a roughness length of 1 cm. Wind and turbulence parameters were derived from 30 min intervals, while the additionally needed boundary layer height was taken from the closest point of the Era-Interim meteorological reanalysis (*Dee et al.*, 2011).

### 2.4 Topographical survey

We conducted a topographical survey of the Adventdalen ice-wedge site employing photogrammetry of aerial photographs to produce a visual map and digital elevation model. To this end, 135 photographs were taken with a camera (GoPro Hero3+ Black Edition) from a UAV (DJI Flamewheel 550) at a height of 60 m a.g.l. in June 2015. This survey covered an area of about 0.1 $km^2$ at a ground resolution of about 3.2 cm $pixel^{-1}$. 22 ground control points were collected with a differential GPS (Leica GPS1200 SmartRover) to ortho-rectify the images and estimate the uncertainty of the resulting elevation model (see Fig. S5 in the supporting information for details). GPS data were post-processed and differentially corrected using data from the local Longyearbyen GNSS satellite basestation (LYRS), which is freely available from the Norwegian Mapping Authority. The photogrammetric processing was performed using Agisoft PhotoScan (Agisoft LLC, St. Petersburg, Russia), which implements the structure-from-motion technique to reconstruct the 3D geometry of the ground surface from the sequence of photographs taken from multiple viewpoints (*Ullman*, 1979; *Snavely et al.*, 2008; *Westoby et al.*, 2012; *Lucieer et al.*, 2014).

To assess the evolution of the morphology of the ice-wedge site, we compared our map from 2015 to historical aerial photographs taken 1948, 1961 and 1990, which were geo-referenced with 2015's map as a reference. Reliably quantifying the changes between these images was complicated by different shadows and overall soil moisture when the images were taken, so we only performed a qualitative change detection by visual comparison.

## 3 Results

Figure 1 shows the results of the topographical survey and the EC footprint for June 2015. As the wind direction typically aligns with the valley's direction, there are two clearly distinct footprint areas in the NW and ESE. The high resolution of this elevation map resolves small elevation differences of only a few decimeters, which can be seen to affect surface inundation and soil wetness. Both footprints have overall surface slopes toward the edge of the river terrace in the north (approximately 0.75% slope), but their drainage patterns appear to be separated creating a wetter sub-catchment in the NW than in the ESE. Low-centered polygons dominate the site, but the NW features more distinctly wet polygon centers. The thaw depth at the centers

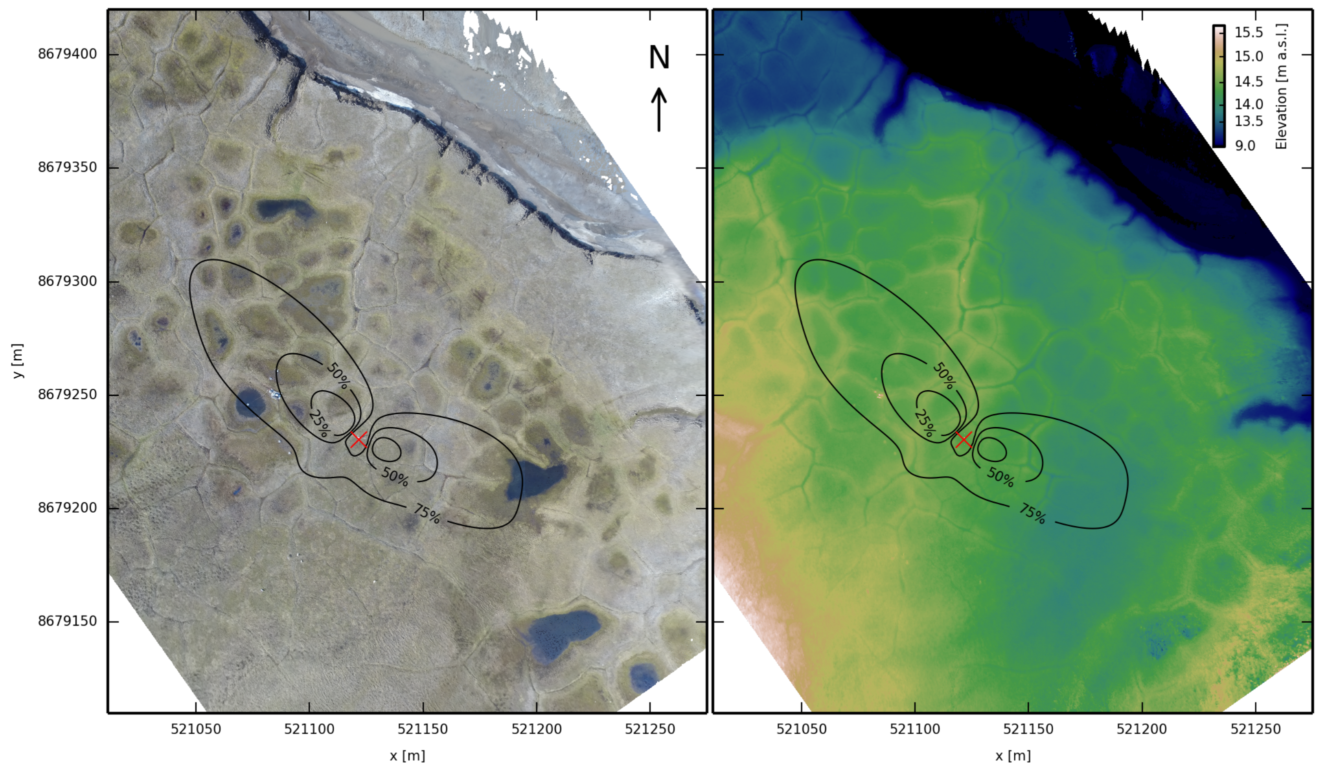


**Figure 1.** Map of the site in Adventdalen (coordinates in UTM zone 33X). The red cross marks the EC tower, around which the contour lines indicate the area's relative contribution to the EC signal (footprints) averaged over June 2015. Six automatic flux chambers are located in the NW footprint (bright dots). Left: Ortho-rectified aerial photograph from end of June 2015. Right: Corresponding surface elevation with an estimated vertical uncertainty of 0.2 m.

of the polygons around the EC tower was ~~on average~~ 66~~cm (standard deviation=~~ cm ±9~~cm~~ cm (mean ±standard deviation, sample size N=30) by the end of August. Based on the polygons in the 50% EC footprint, the drier ESE fetch area ~~had on average 10 cm larger thaw depths than~~ featured a thaw depth of 69 cm ±8 cm (N=4) while the wetter NW ~~, but due to the large variations this difference is not statistically significant~~featured 79 cm ±4 cm (N=4), which is not a statistically significant difference (p=0.10).

The shown surface heterogeneity is likely to lead to spatial variations of NEE in the EC footprint. To assess this effect and mesoscale disturbances, we investigated the spectral composition of the EC signal by looking at the ogives of vertical wind speed and $CO_2$ concentration. Particularly around the time of snowmelt, we often found a mismatch between lower and higher frequencies indicating different local and non-local flux contributions. Figure 2 ~~a~~ shows an example from this period comparing the ogives of conventional flux calculations produced by EddyPro and ogive optimization flux estimation based on the ogive density map. While all frequencies contribute fully to the conventional flux estimation, frequencies can obtain less weight in

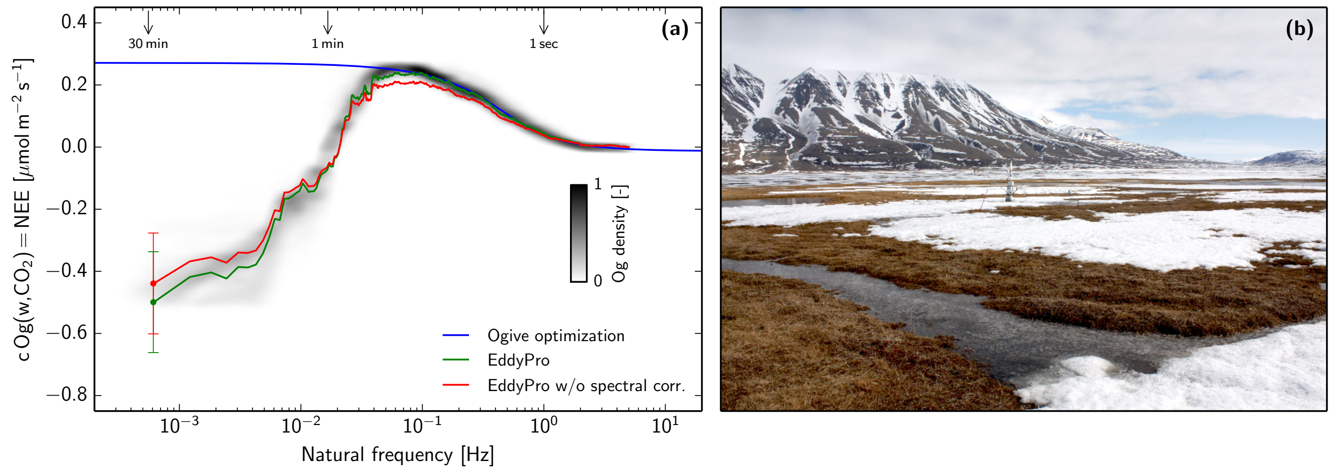


**Figure 2.** Example of the $CO_2$ flux estimation during snowmelt. a: ~~Ogives~~ Ogive on 31 May 2015, 15:00 LT, showing a mismatch between low and high frequencies. While ogive optimization estimates a net $CO_2$ release, EddyPro (with and without spectral corrections after *Moncrieff et al.* (1997, 2004)) indicates an uptake. Average horizontal wind speed was 5.2 m ~~secs~~$s^{-1}$ from NW (313°), air temperature 4.5°C, quality flag 0. Arrows on the top indicate the corresponding time scales. b: Photo of the environment around the flux tower ~~at that time~~on 27 May 2015, 12:00 LT during snowmelt.

the ogive optimization method if they cannot be described by the ogive spectral distribution model. In the given example, this conceptual difference of the methods means that ogive optimization indicated a $CO_2$ release, while EddyPro indicated uptake. Spectral corrections had a comparably small effect. The ogive optimization model indicates that all relevant flux contributions are carried by turbulence with a scale shorter than about 25 s in this example (which does, however, not mean that 25 s are in general enough to determine a 30 min flux). During this period in May and June the surface was a mix of patches of snow-free soil, remaining snow, and meltwater ponds (when a net $CO_2$ uptake can be considered unlikely, see Fig. 2b). The ~~low frequency~~ low-frequency contributions also depend on larger-scale atmospheric movements, while the local turbulent flux is represented better in the mid-to-high frequency range. Such frequency mismatches (high-frequency $CO_2$ release, but low-frequency uptake) were frequently observed in our data and their effect was relatively largest for the small non-growing season fluxes (see Fig. S1 in the supporting information for additional ogive examples and Fig. S3a for a flux comparison). The shifts between release and uptake of $CO_2$ typically occurred at frequencies below $10^{-1}$ Hz, corresponding to recorded eddies with a diameter of typically more than 30 m at the given wind speed. During the growing season, fluxes from both methods typically agreed. Photos of the site in different seasons are given in Fig. S6 in the supporting information.

~~Due to its better performance, we used~~ Since the frequency mismatches cannot be resolved in conventional calculations, we focus on the NEE fluxes calculated by the ogive optimization method for the ecosystem characterization. Figure 3 shows the gap-filled NEE fluxes of 2015 as fingerprint plots, as well as cumulative sums, which were also calculated after separately gap-filling the measurements of the two distinct footprints (NW and ESE). These results indicate that the growing season in 2015 started on 14 June and ended 28 August (defined as first until last day of net $CO_2$ uptake). Results from EddyPro indicated the same date for the end of the growing season, while its start was suggested already one month before snowmelt. The fingerprint plot (Fig. 3a) shows that there can even be $CO_2$ uptake at midnight during the polar day in the summer. While the drier ESE yielded an annual carbon balance of $-62$ gC m$^{-2}$, the wetter NW yielded $-91$ gC m$^{-2}$. The annual balance of the combined footprint (using all fluxes without separating periods of different wind directions) was $-82$ gC m$^{-2}$ in 2015. The corresponding value based on EddyPro flux calculations was $-128$ gC m$^{-2}$, which we consider biased by the above-mentioned low frequency low-frequency contributions. The relatively narrow probability distributions of the annual sums (based on gap-filling uncertainties) demonstrate the significance of the differences between the NW and ESE footprints, as well as between the ogive optimization and EddyPro methods. Relatively large annual sinks are supported by our automatic closed chamber measurements in the NW footprint which show good agreement and correlation ($0.75 < r < 0.88$, $p < 10^{-12}$ $p < 0.0001$) with the EC fluxes (see Fig. S3b in the supporting information). In 2013, EddyPro calculations yielded a smaller total annual $CO_2$ balance of $-79$ gC m$^{-2}$ (see Fig. S2d in the supporting information), whereas ogive optimization fluxes could not be calculated from these 2013's raw $CO_2$ measurements since they were wet rather than dry molar densities. (cf. section 2.3).

Much of the spatial differences in the annual $CO_2$ budget stem from the growing season, when NEE is strongly affected by PAR. Figure 4 shows examples of the derived light response curves, as well as the evolution of the associated dark respiration and light-use efficiency throughout the growing season. Both dark respiration and light-use efficiency were typically higher in the wetter footprint (NW) than in the drier (ESE), consistent with the larger annual uptake in the NW than the ESE. At the beginning and end of the growing season, the determination of the flux at light saturation ($F_{\mathrm{csat}}$) was associated with relatively large uncertainties, because NEE and PAR varied relatively little. During the peak growing season $F_{\mathrm{csat}}$ was about 6.6 $\mu$mol m$^{-2}$ s$^{-1}$ for both footprints. The sum of $F_{\mathrm{csat}}$ and $R_{\mathrm{d}}$ can be used to estimate the gross primary productivity at light saturation, which was found to be $-11.0$ $\mu$mol m$^{-2}$ s$^{-1}$ in the NW and $-8.3$ $\mu$mol m$^{-2}$ s$^{-1}$ in the ESE. During snow covered conditions outside the growing season, our measurements indicated an overall decreasing trend of the small $CO_2$ releases throughout winter, which was modulated by increases during strong winds (see Fig. S4 in the supporting information). Soil temperature, on the other hand, had no strong effect on the wintertime $CO_2$ release despite a large variation of more than 25°C K (cf. Fig. S4c).

Figure 5 shows a time series of ortho-rectified aerial photographs covering the same area as Fig. 1. Despite the differences in image quality, shadows and overall soil moisture on the days these images were taken, the time series still gives an impression about the development of the polygon morphology. All images show the same, low-centered polygons, whose centers were about equally inundated (except in 1990 when the area was drier in general). There was no clear lateral expansion or degradation of the polygon troughs. Neither the ponds nor the troughs became more interconnected or wet in general, so there are no clear signs of differential ground subsidence at this site. Also other areas with ice-wedge polygons in Adventdalen indicated the same, stable morphology during the last seven decades (see Fig. S7 in the supporting information). Between 1990 and 2015, some erosion on the edge of the river terrace occurred. The exact speed of this edge erosion is hard to quantify due to the shadows in this area, but it did not exceed 3 m over these 15 years. The photograph from 1990 was taken in the near infra-red range and is shown in false colors. Vegetation, bare soil, and open water reflect near infra-red light differently, so this image

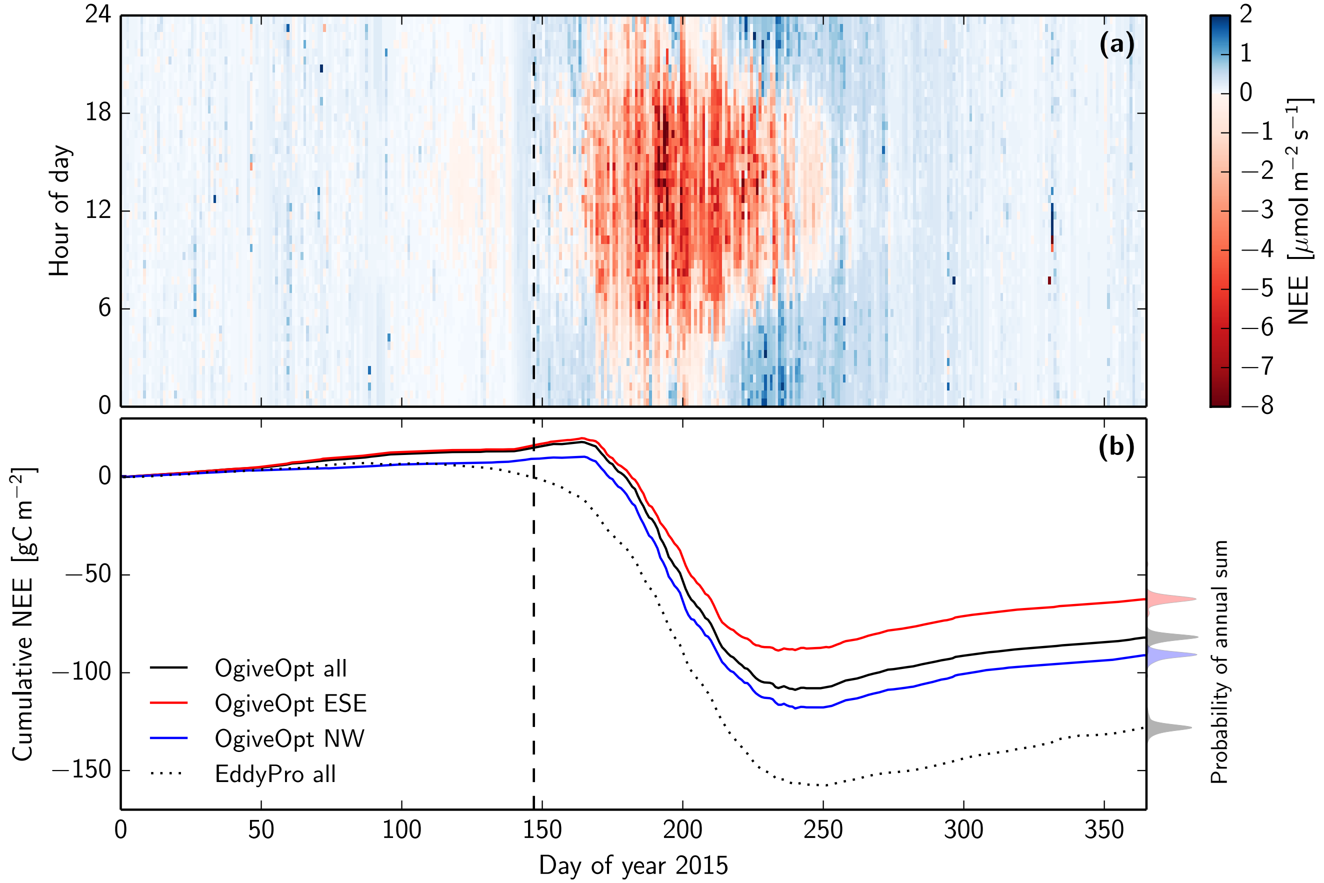


**Figure 3.** Gap-filled NEE fluxes for 2015. a: Fingerprint plot of ogive optimization results. b: Corresponding cumulative sums based on all valid measurements (black), and separately gap-filled for the two footprints (colored). The probability distributions shown on the right indicate the estimated uncertainty of the annual sum due to data gaps and gap-filling. The dashed line marks the time during snowmelt when daily average albedo dropped below 0.3 (27 May 2015).

clearly depicts these surfaces. The strong red tones in the NW footprint correspond to the relatively high vegetation density in this area, which was also seen in Fig. 1. The river in the NE appears in a blue tone, while darker spots in the SW corner of the image correspond to an area with bare soil brought to the surface by cryoturbation.

## 4 Discussion

Our measurements demonstrate the high sensitivity of carbon cycling to small topographic differences in permafrost-underlain Arctic tundra. Ice-rich permafrost is particularly vulnerable to warming, with large increases in permafrost degradation documented in the last two decades (*Jorgenson et al.*, 2006; *Osterkamp et al.*, 2009; *Grosse et al.*, 2011). *Liljedahl et al.* (2016)

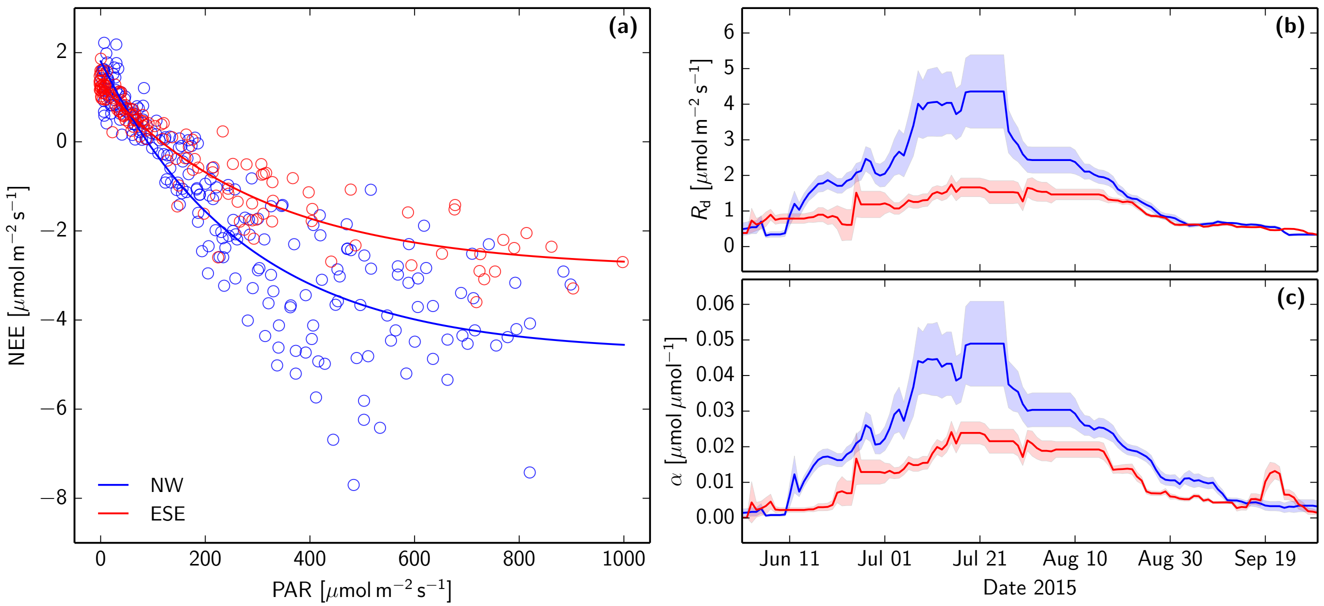


**Figure 4.** Growing season NEE light response curves based on the ogive optimization method. a: Examples from the time window around 18 August 2015 from the two distinct footprints. b: Time series of dark respiration parameters. c: Corresponding graph for light-use efficiency. Shaded bands indicate the statistical standard error of the parameters.

observed pan-Arctic permafrost degradation in polygonal tundra which dramatically changed the local drainage patterns and water balance on sub-decadal timescales. Ice-wedge melting and the associated differential ground subsidence is expected to interconnect formerly separated trough networks and thereby increase the drainage of polygon centers (*Necsoiu et al.*, 2013; *Jorgenson et al.*, 2015; *Liljedahl et al.*, 2016). At a later stage this process transforms low-centered polygons into high-centered polygons and leads to the overall drying of the entire landscape. In such cases, the space-for-time substitution of our two distinct footprint areas in Adventdalen would suggest a corresponding lessening of $CO_2$ sinks in degrading polygonal tundra.

However, our comparison of aerial photographs taken between 1948 and 2015 shows that there is no dramatic ice-wedge degradation at our site on Svalbard. Nearby areas with polygonal tundra in Adventdalen have also been stable during the last seven decades, despite the measured increase of 2.95°C in mean annual air temperatures between the periods 1961–1990 and 2000–2011 (*Førland et al.*, 2012; *Christiansen et al.*, 2013; *Nordli et al.*, 2014). The maritime climate on Svalbard prevents episodes with extremely high summer temperature, which have been hypothesized to trigger ice-wedge degradation (*Jorgenson et al.*, 2006; *Liljedahl et al.*, 2016). It appears that the gradual climate warming alone has so far not been sufficient to initiate strong ice-wedge degradation in Adventdalen. Another reason for the apparent stability of the ice wedges at our site could be the relatively small surface slope of typically less than 1%, which hinders the development of an effective drainage system of degraded troughs. Generally speaking, ice-wedge stabilization can also be caused by negative feedbacks such as increased plant growth in degraded troughs which cools the soil above the ice wedge (*Jorgenson et al.*, 2015). Despite these mechanisms

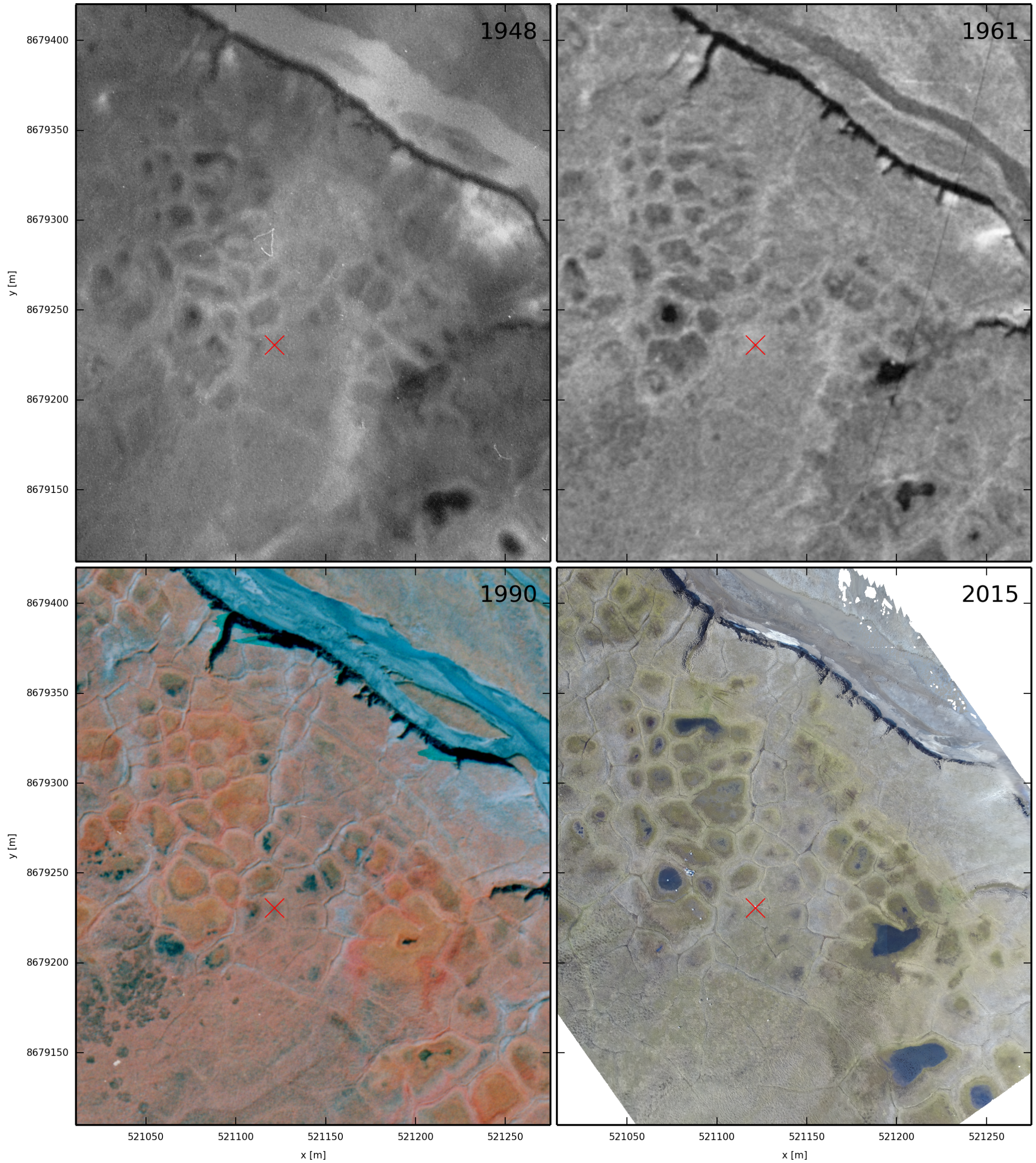


**Figure 5.** Time series of images of the Adventdalen site showing little signs of differential ground subsidence, which would indicate ice-wedge degradation. The image from 2015 is the same as shown in Fig. 1, while historical photographs were provided by the Norwegian Polar Institute (reference numbers S48-5181, S61-3301 and S90-5273). The images from 1948 and 1961 were taken on panchromatic films, and the image from 1990 is a near infra-red (false color) photography. The red cross marks the EC tower.

and observations, the strong temperature increase on Svalbard may eventually lead to the gradual degradation of ice wedges in Adventdalen, which we argue will lessen the $CO_2$ sink of this ecosystem.

The overall annual $CO_2$ balance of $-82$ gC m$^{-2}$ seems surprisingly large, given the high northern location of the site with its typically shallow organic horizon in the soil (5–10 cm). The good agreement of EC and automatic closed chamber measurements, however, confirms the relatively high uptake fluxes in the snow-free period. Also the comparison of the light response curve parameters to other Arctic sites indicates high, but realistic, growing season productivity. *Mbufong et al.* (2014) derived these parameters from 12 Arctic tundra sites during the peak growing season and report $R_\mathrm{d}$ between 0.6 and 3.9 $\mu$mol m$^{-2}$ s$^{-1}$, and $\alpha$ between 0.011 and 0.057 $\mu$mol $\mu$mol$^{-1}$. Peak season parameters for the drier footprint (ESE, $R_\mathrm{d}$ ~1.7 $\mu$mol m$^{-2}$ s$^{-1}$, $\alpha$ ~0.024 $\mu$mol $\mu$mol$^{-1}$) at the Adventdalen site lie well in the center of this range, while the wetter footprint (NW, $R_\mathrm{d}$ ~4.3 $\mu$mol m$^{-2}$ s$^{-1}$, $\alpha$ ~0.049 $\mu$mol $\mu$mol$^{-1}$) lies on the upper end of this reported range. These values, in combination with the relatively large amount of incoming shortwave radiation at 78°N during summertime, explain the large carbon sink in Adventdalen. The summertime $CO_2$ sink of Adventdalen is comparable to this season's $CO_2$ balance at a coastal wet sedge tundra ecosystem at Barrow, Alaska ($-105$ to $-162$ gC m$^{-2}$) (*Harazono et al.*, 2003). Especially the wetter areas lose some carbon through methane emissions, but ~~our~~ automatic chamber measurements at Adventdalen indicate that these losses are not expected to exceed 6 gC m$^{-2}$ per year (*Pirk et al.*, 2016a). We consider the export of dissolved organic carbon negligible, because the small surface slope and limited conductivity prevents a pronounced lateral water runoff.

The grazing pressure from Svalbard reindeer could represent another type of carbon loss, which has not been quantified in the present study. Moreover, *Wegener and Odasz-Albrigtsen* (1998) observed that plants in Adventdalen balance the consumption by reindeer with increased plant productivity. While such interactions influence the carbon budget of the ecosystem, they do not affect the discrepancy we found between the two EC flux calculation methods.

The drivers of cold season emissions of $CO_2$ from high Arctic tundra are still understudied, because technical challenges and low flux magnitudes often complicate continuous in-situ flux measurements. Our wintertime flux measurements from Adventdalen were found to decrease slightly throughout winter. Episodic flux increases correlated with wind speed, suggesting a convective mixing of the snowpack gas reservoir as observed in other studies from lower latitudes (*Takagi et al.*, 2005; *Seok et al.*, 2009; *Smagin and Shnyrev*, 2015). The missing relation between soil temperature and measured wintertime $CO_2$ release could suggest a decoupling of $CO_2$ production and release caused by the physical blockage of gas diffusion in the soil (*Elberling and Brandt*, 2003) or through potential ice layers in the snowpack (*Pirk et al.*, 2016a). While the majority of wintertime fluxes were positive, some small uptake fluxes have also been observed during the dark, snow covered period. Unlike reports from other sites (*Lüers et al.*, 2014), these fluxes have no significant impact on the annual $CO_2$ budget of our site. As photosynthesis by plants or snow algae can be excluded during the dark polar night, one might speculate that the apparent uptakes are caused by abiotic mechanisms, such as the convective mixing of $CO_2$-depleted gas stored in the snowpack or thermo-physical processes related to $CO_2$ solubility in unfrozen pore water. Yet we found no relationship between uptake situations and changes in snow, air or soil temperatures, or ambient atmospheric $CO_2$ concentrations—which could support potential abiotic mechanisms of $CO_2$ uptake. The magnitude of these fluxes was also so low compared to biotic flux contributions that they cannot markedly change the overall annual $CO_2$ balance of the ecosystem and remain to be regarded as noise in this study.

The conceptual definition of turbulent fluxes differs fundamentally between the ogive optimization and conventional methods as implemented in EddyPro. While the ogive optimization assumes a unidirectional flux, which is sometimes better captured in the mid and ~~high frequency~~ high-frequency range, EddyPro includes all frequencies regardless of their direction. The ogive optimization method appeared better suited for the Adventdalen site than conventional processing schemes. Specifically around the snowmelt period, the ogive optimization estimates appear to capture the local flux signal more realistically than conventional calculations, which indicated an onset of the growing season already before snowmelt. This contradiction was caused by many bi-directional fluxes, i.e. situations with a consistent $CO_2$ release reflected in high frequencies and $CO_2$ uptake reflected in the ~~low frequency~~ low-frequency range of the spectrum (cf. Fig. 2 ~~a~~ and Fig. S1). The shift between these contributions occurred at frequencies corresponding to eddies with a diameter of more than 30 m, i.e. exceeding the typical dimension of surface heterogeneity in the footprint area of our site. However, we cannot fully exclude that the frequency mismatches are caused by flux heterogeneity within the local footprint. It could be possible that the drier areas near the EC tower (reflected better in the high frequencies) are net $CO_2$ sources, while wetter areas at larger distances from the tower (reflected in the low frequencies) are net $CO_2$ sinks. A heterogeneous vegetation composition might cause such flux heterogeneity during snowmelt, because unlike shrubs and sedges, mosses have photosynthetically active tissue that may overwinter so that they can start photosynthesizing at low rates already during snowmelt (*Oechel*, 1976; *Tieszen et al.*, 1980). While some degree flux heterogeneity is certainly present at any time of year, its effect might be too small to explain the large frequency mismatches observed particularly during snowmelt. Nevertheless, our observations might incentivize future studies to investigate the frequency dependency of EC footprints. Snowmelt also entails a change in the typical surface roughness length, which is slightly smaller for snow than open tundra vegetation. A greater roughness could break down larger turbulence into smaller turbulence, thus shifting some of the flux co-spectrum toward higher frequencies. However, such spectral shifts would be no problem for the functionality of the used flux calculation schemes and cannot readily explain bi-directional fluxes even if the surface roughness is spatially heterogeneous. One might speculate that the systematic occurrences of bi-directional fluxes are due to an atmospheric layering where low and ~~high frequency~~ high-frequency eddies circle through air masses with different atmospheric stability and $CO_2$ concentrations: While the (smaller) ~~high frequency~~ high-frequency eddies only reflect one air mass, the (larger) ~~low frequency~~ low-frequency eddies reflect two air masses with different $CO_2$ concentrations. In the specific environment in Adventdalen, such a layering might be induced by the intrusion of $CO_2$-depleted air at the surface originating from the surrounding mountains by way of katabatic winds, or sea breeze circulations from the nearby fjord (*Esau and Repina*, 2012). However, similar ~~low frequency~~ low-frequency shifts were also observed in environments with neither pronounced surface heterogeneity nor nearby water bodies, snow or mountains (*Sievers et al.*, 2015b), as well as in temperate regions (*Finnigan et al.*, 2003). Across the different sites we see a tendency for ~~low frequency~~ low-frequency shifts to occur predominantly during conditions with small flux magnitudes, when the normally dominating mid and ~~high frequency~~ high-frequency contributions can be much smaller than (non-local) ~~low frequency~~ low-frequency contributions. So perhaps the hypothetical layering of the atmosphere is caused by the repeatedly changing $CO_2$ flux at the surface in response to diurnal factors such as changes in incoming solar radiation, which give rise to $CO_2$ concentration waves propagating vertically into the atmosphere. While such hypotheses remain to be investigated in future studies, we show that these (non-local) ~~low frequency~~ low-frequency contributions lead to a difference in the annual $CO_2$ budget of $-46$ gC m$^{-2}$ over the course of one year (cf. Fig. 3b). The ogive optimization method is more applicable to these highly heterogeneous, Arctic environments dominated by small fluxes because it can separate local and non-local flux contributions.

## 5 Conclusions

The Adventdalen ice-wedge site was a surprisingly strong $CO_2$ sink in 2015 ($-82$ gC m$^{-2}$). Differences in vegetation density and composition lead to a significantly higher light-use efficiency in areas with low-centered ice-wedge polygons compared to flat-centered polygons. While dark respiration in the wetter area was also higher than in the drier area, these releases did not compensate for the higher light-use efficiency in the annual $CO_2$ balance. In 2015, the drier area sequestered 32% less $CO_2$ than the wetter area ($-62$ compared to $-91$ gC m$^{-2}$). These results suggest a high sensitivity of $CO_2$ dynamics to small topographic differences in Arctic tundra ecosystems. With climate warming, ice wedges are predicted to melt and dry out the landscape. Despite strong increases in mean annual air temperatures of more than 2°C on Svalbard in the last few decades, we see no evidence of ice-wedge degradation compared to historical aerial images. However, further warming may eventually initiate ice-wedge degradation, and our spatial analysis implies a corresponding reduction of the $CO_2$ sink upon drying. In Arctic polygonal tundra where drying is occurring already, our results therefore suggest a similar weakening of the $CO_2$ sink function.

## 6 Data availability

Maps, measurement data and processing scripts are available from the authors upon request (norbert.pirk@nateko.lu.se).

*Competing interests.* The authors declare that they have no conflict of interest.

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