Final author response to **"Exchange of CO2 in Arctic tundra: impacts of meteorological variations and biological disturbance"**

Efrén López-Blanco, Magnus Lund, Mathew Williams, Mikkel P. Tamstorf, Andreas Westergaard-Nielsen, Jean-François Exbrayat, Birger U. Hansen, Torben R. Christensen

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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, and attached a marked-up manuscript version showing the differences to the initially submitted version. Please note that the line numbers point to the non-marked manuscript.

Interactive comment on "Exchange of CO2 in Arctic tundra: impacts of meteorological variations and biological disturbance" by Efrén López-Blanco et al. Anonymous

Referee #1

Received and published: 17 May 2017

Lopez-Blanco and colleagues present a study of ecosystem CO2 dynamics across eight snow-free seasons for a wet fen tundra ecosystem in west Greenland. The authors compare ecosystem respiration (Reco) and gross primary production (GPP) with key climatic drivers to characterizes how ecosystem CO2 dynamics will change with climate. Comparisons are made at hourly, daily, and seasonal timescales to understand how drivers of ecosystem CO2 dynamics change across temporal scales. Additionally, the authors compare several eddy covariance partitioning methods in order to assess uncertainty associated with interpretation of EC derived estimates of Reco and GPP. The main finding is that large interannual variations in Reco and GPP with climate are compensatory, and so net ecosystem exchange (NEE) of CO2 remains quite stable across climatically diverse snow-free seasons. This is a valuable analysis of a fairly long EC data set, particularly for a tundra ecosystem. Overall I find the methodology to be quite sound and recommend several relatively minor but important revisions before the manuscript is considered further for publication. The following paragraphs describe more major issues, and are then followed by specific comments.

We thank the reviewer for taking the time to assess our manuscript. We believe the comments have improved the manuscript. We carefully considered each of the comments, paying special attention to the structure of the paper and the implications and the transferability of our findings.

The introduction should be improved in several ways. First, the paragraph on flux partitioning seems out of place. The first and third paragraphs highlight research surrounding tundra/Arctic C cycling, and are bisected by the paragraph on partitioning. It would make more sense to first discuss carbon cycle dynamics and then highlight challenges associated with EC partitioning; so switch paragraphs two and three.

The reviewer is correct that the paragraphs 2 and 3 should be inverted. The introduction has been modified based on the referee comment (L47-63). Moreover, we moved the information about the measurements to the materials and methods section (L105-109). Further, we included our overarching hypothesis at the end of the introduction (L83-85).

In the results it seems that sections 3.3 should come before section 3.2; first describe the partitioning comparisons and then get into the results. Related, I don't see where you mention which partitioning/gapfilling methods you report. It would make sense to first present the flux processing results, and then state

which date you'll present moving forward. Also, it is general good to have the figures ordered as they appear in the text. Currently order is Fig 5 -> Fig 4 -> Fig 3.

The reviewer is correct that the sections 3.2 and 3.3 should be inverted. The results section has been improved. Now the partitioning/gapfilling method is presented before the results (L219-238).

Further, the figures have been ordered as they appear in the text.

The last major area for revision is related to the broader implications of your results – specifically, how transferable are they? There is some of this in section 4.3, but it could be expanded there, and perhaps in section 4.1. Specifically, it occurs to me that this research site receives a relatively high amount of precipitation relative to many other tundra ecosystems, and has no permafrost. As such, the NEE responses to climate at other tundra sites may likely be more variable. It would be worth discussing this a bit further.

Text has been revised and implemented to focus on the implications of our results (L332-347):

> Interestingly, the tendency to warmer and wetter conditions led to greater rates of C cycling associated with larger GPP and R_{eco} (Figure S3; supplementary material). This result does not entirely coincide with Peichl et al. (2014), even though they performed a similar analysis for a Swedish boreal fen. This finding points towards the complexity in the response of wetland ecosystems towards changing environmental conditions. The response is dependent on many things, such as hydrological settings, and these differ between sites. In this study, larger rates of C uptake (GPP) were linked to larger rates of C release (R_{eco}), with the exception of the anomalous year 2011. The relative insensitivity of NEE to meteorological conditions during the snow-free period could be the result of the correlated response of ranked cumulative GPP and R_{eco} (Figure 5) (Richardson et al., 2007; Wohlfahrt et al., 2008). This site likely receives more precipitation relative to many other tundra ecosystems, and has no permafrost, thus the NEE response to climate could be less variable. However, as Kobbefjord is located in a coastal area, it is not surprising to receive high precipitation, and other ecosystems such as coastal blanket bogs often receive even more precipitation without a clear impact of drought effect on the NEE sensitivity (Lund et al., 2015). Furthermore, permafrost adds another layer of complexity to the C dynamics (Christensen et al., 2004; Koven et al., 2011; Schuur et al., 2015). Although some studies showed similarities of CO_2 fluxes in various northern wetland ecosystems with and without permafrost (Lund et al., 2015), permafrost has strong influence on the hydrology of peatlands (Åkerman and Johansson, 2008), and therefore their topography and distribution of vegetation (Johansson et al., 2013). Especially in the context of climate warming permafrost thaw can cause large changes to the ecosystems.

Secondly, it is difficult to talk about ecosystem CO2 source/sink dynamics without some discussion of non-growing season processes. Papers by Zona et al and Commaine etal (very recently) indicate the importance of non-growing season C dynamics. Also, given the fact that you are using net sink timing to define the growing season, I wonder what effect previous growing season or

previous winter conditions might have on your results? For example does a wet summer followed by a warm winter lead to high Reco the following year? There are very likely some interesting time-lag effects influencing the patterns you observe. Again, you allude to these processes, for example, by mentioning previous winter temperatures, but I think a more targeted and thoughtful discussion on temporal lags/dynamics would be useful. Actually, it would be helpful to report non-growing season climate data, and perhaps even analysis of these sorts of time lags. I do not think the latter is absolutely necessary, because this paper already contains a lot of information, but it could be informative either here or in another paper.

We have adjusted Figure 2 and the corresponding text in the results section to include meteorology from non-growing season, including preceding cold season (October to May) and warm season (June to September) (L720-725).

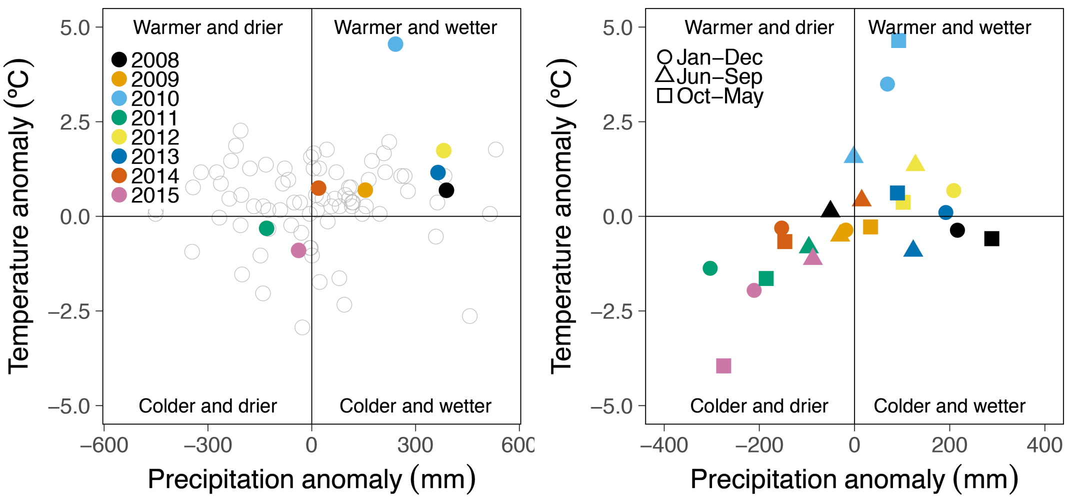

Figure 2: (a) Annual Temperature (°C) and precipitation (mm) anomalies of the analyzed years (2008-2015) compared to the 1866-2007 time series shown as empty circles (Cappelen, 2016), and (b) within the 2008-2015 period including annual (January to December), warm season (July to September) and cold season (October to May) averages.

Moreover, we supported the Figure with more text (L206-210):

> Among the eight study years (figure 2b), the warm season (June to September) temperature and precipitation anomalies ranged from approx. -1°C (2011, 2013 and 2015) to +1.5°C (2010) and -96 mm (2011) to approx. +125 mm (2012 and 2013), respectively. The cold season (October to May) anomalies have shown a significant increase of both temperature and precipitation variability. 2010 was the warmest year while 2011 and 2015 were the coldest years.

Further, some text has been implemented in the discussion l372-383:

> A combination of different factors could have led to the sharp change in C balance observed between 2010-2011, both physical and biological. The year 2010 had the warmest mean annual temperature (3.4 °C compared to the -0.4 °C mean annual

temperature for 2008-2015) and the warmest mean wintertime temperature (-2.7 °C compared to the -6.79 °C mean for 2008-2015) (Figure 2a). These climatic conditions generated the thinnest (maximum daily snow depth of 0.3 m compared to averaged 0.9 m) (Table 1) and shortest-lasting snowpack. Consequently, 2010 had the longest growing season (85 days) and very high growing season C uptake (-70 g C/ m^{-2}). Increases in temperature can lead to high respiration rates during early winter (Commane et al., 2017; Zona et al., 2016), but also during the following summer (Helfter et al., 2015; Lund et al., 2012), which is related to soil temperature and snow dynamics. Further, in Kobbefjord the year 2011 had one of the lowest mean annual temperatures and mean wintertime temperatures (-1.7 and -6.1°C respectively), which created the thickest (maximum daily snow depth of 1.4 m) and the longest-lasting snowpack, leading to the shortest growing season for the study period (only 47 days). According to Lund et al. (2012), below thick snowpack soils will be insulated from reaching low temperature, acting as lid and preventing R_{eco} from being released to the atmosphere until the snowmelt period.

Finally, we understand the referee's point about the importance of non-growing season climate implications. Winter fluxes are beyond the scope of this paper, since it is hard to analyse only eight-years dataset, but that an ongoing modelling effort will seek to address these issues. The referee comment will be a good point to address in this coming paper.

(I will also note here that it seems odd to place the section on EC processing between to two sections discussing CO2 dynamics).

The sections have been inverted accordingly.

Minor edits:

- **Lines 40-44: You should explicitly state that you are referring to soil C stocks – this doesn't come until the very end.**

  Now corrected.

- **Line 76: Why do you mention C a need for sites with C stocks if you don't present them in the paper?**

  Although it is highly interesting to measure C stocks in the field, the reviewer is correct that we don't present C stocks data in this paper. Therefore, we decided to remove this part.

- **Line 102: This line is a bit too informal; it's not Skip's map, it was a large collaborative effort. It would be more appropriate to report the class and the name of the map and the paper describing the map. Walker, D. et al. (2005), The Circumpolar Arctic vegetation map, Journal of Vegetation Science, 16(267-282).**
- **Lines 103-104: I don't understand this, what does it mean that the site 'went out of the Arctic zone'?**

  Both parts have been adjusted accordingly L96-100:

Kobbefjord belongs to the "Arctic Shrub Tundra" (bioclimate zone E) according to The Circumpolar Arctic Vegetation Map (CAVM Team, 2003; Walker et al., 2005). This map is based on the summer warmth index (SWI), which is the sum of the monthly mean temperature above 0 °C from May to September and the southernmost bioclimatic zone E has the limits 20-35. In 2010 and 2012, climate conditions led the area to experience temperatures from warmer climatic zones (SWI ca. 36 and 35 respectively).

- **Line 142: What is Papale et al In Prep? Perhaps indicate that this is via personal communication as well, if that is the case.**

  Reference deleted.

- **Line 264: This is a very simplistic and incomplete view of the residence time of fixed C. I'm not sure you can say anything meaningful about C residence time with discussing fluxes between pools and storage, which aren't really addressed in this manuscript.**

  Net flux information alone is not enough to determine residence times, which depend on internal flows, dynamics and pool sizes. So we adjusted this text to remove the discussion around residence times.

- **Line 279: This could be worded clearer; at first I thought you were saying the PAR values peak at 6am, which was confusing. Perhaps explicitly state that the predictive importance of PAR peaks at this time.**

  Sentence adjusted accordingly (L281): "*PAR was important at dawn (06 h. WGST) and dusk (15-17 h. WGST), while T_{air} was more important at other times*".

- **Line 287: The model 'catching' something is perhaps a bit too colloquial. Better to state that it revealed or indicated a decline in the importance of PAR in 2011.**

  The text has been changed (L292) to "the Random Forest analysis revealed a decrease of PAR's importance in 2011".

- **Line 295: You can only say that NEE is insensitive to climate during the snow-free season.**

  Sentence implemented.

- **Line 300: 'NEE exchange' is redundant, just use NEE (here and elsewhere).**

  Corrected.

- **Line 330: Lots of typos here.**

  Thanks for finding these two errors; now corrected.

- **Figures 4 & 7: It would be good to include a legend indicating what the colors represent, in addition to the text description.**

  The legend has been updated in both Figure 4 (L731) and 7 (L742). In Figure 4, the facets' labels on the right have been increased in size as well for readability purposes. Moreover, it has been modified the colours of air temperature and precipitations, as well as the direction of the facets on the right. Further, Figure 8 (L748) has been also harmonized colour wise with respect Figure 7.

Interactive comment on Biogeosciences Discuss., doi:10.5194/bg-2016-506, 2016.

Interactive comment on “Exchange of CO2 in Arctic tundra: impacts of meteorological variations and biological disturbance” by Efrén López-Blanco et al. Anonymous

Referee #2

Received and published: 29 June 2017

The article “Exchange of CO2 in Arctic tundra: impacts of meteorological variations and biological disturbance” by Lopez-Blanco and co-authors presents eight years of eddy covariance measurements from a tundra site in Greenland. The data set is rich and the authors apply current and appropriate methods in data analysis to derive gap-filled net carbon fluxes, as well as to partition these fluxes into the photosynthetic and respiration components. The authors attempt to analyze gap-filling procedures and use autochamber data towards these efforts. The undertaken analyses reveal valuable insight into the behavior of tundra carbon cycling in response to environmental variability from hourly to inter annual scales. Novel methods are applied to analyze the role of environmental drivers of C cycling as well as biological factors such as a pest outbreak. In general, the manuscript is a solid and valuable contribution. Greater attention to grammar, structure, and clarity will greatly improve the article. In some cases, additional justification for statements or references to literature are needed. The comments that follow provide suggestions for addressing these concerns before publication.

We are thankful for the reviewer’s insightful comments that have improved the manuscript. We have carefully considered the reviewer’s remarks and clarified our manuscript accordingly.

General comments:
There is too much repetition in portions of the manuscript (specific comments identify some of these sections), and efforts to reduce repetition will increase the readability of the paper.

Taking your advice into account, and also based on your guideline in one the very last specific comments (P10), major efforts have been dedicated to the discussion section, so the outcome is more transferable to literature and less repetitive. It was a priority to improve clarity and readability. We also worked in the paper’s structure. Finally, the conclusions have been reduced to put the key findings in a more general context.

**More attention is needed to grammar throughout the manuscript. Importantly please play close attention to the correct use of singular or plural nouns. Here are some examples where they should be switched (but please address on a case by case basis): Singular case instead: temperatures -> temperature, exchanges -> exchange, bud- gets -> budget, precipitations -> precipitation, references ->

reference, evidences -> evidence Data: plural -> data are rare Capitalize Earth and Arctic when proper nouns

Thanks for finding these errors; now corrected.

With respect to figure 6, what causes the different direction (clockwise vs counter-clockwise) in the hysteresis observed in 2010 vs 2012 vs 2013? It would be interesting to know the whether the causes for early versus late season decoupling of GPP and Reco are the same or different.

This is a very pertinent comment. We implemented the following figure in the supplementary material:

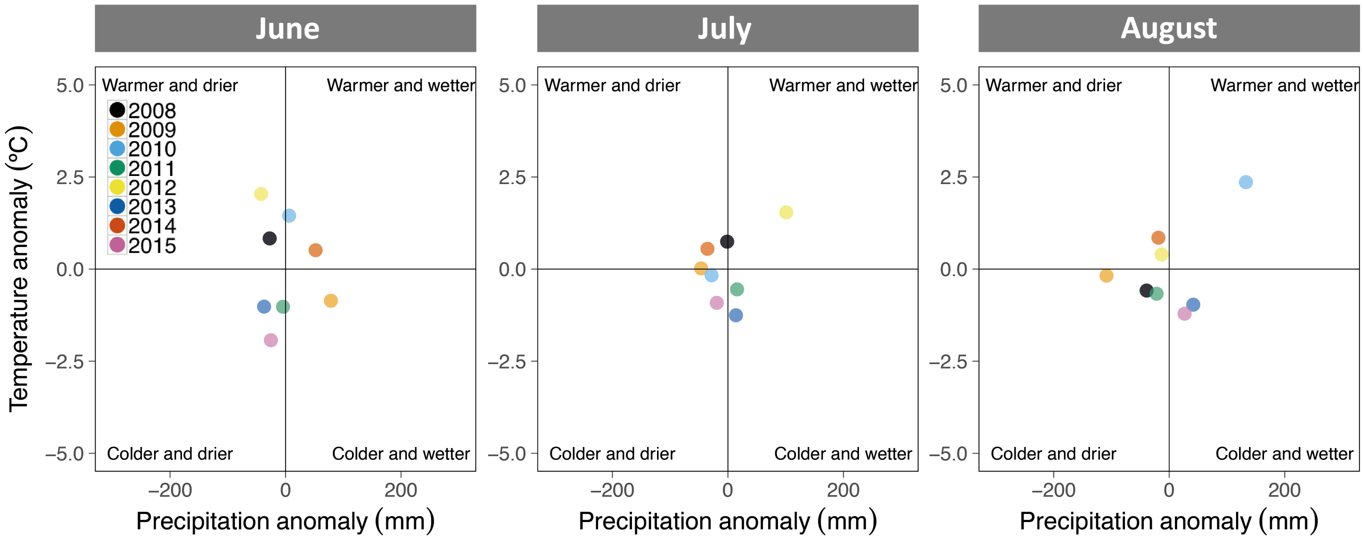

Figure S4: Temperature (°C) and precipitation (mm) anomalies in June, July and August of the analysed years (2008-2015).

Moreover, we implemented the following text in the results section (L269-273):

> It is worth mentioning the different direction (clockwise vs counter-clockwise) in the hysteresis observed these years between June, July and August. The data suggest that the clockwise 2012 hysteresis was due to greater gross C cycling (GPP and R_{eco}) in June and July favored by warmer conditions; while in 2010 (counter-clockwise hysteresis), the higher gross C fluxes have been measured in August with warmer and wetter conditions (Figure S4; supplementary material).

Specific comments:

- **Abstract: I find the use of meteorology and climate to be a bit conflicting here. Please ensure whether you mean meteorology or climate with reference your conclusions in this study.**

  The referee is right; we now maintain consistency in the terminology. Because this is an 8-years dataset, we have decided to use the term meteorology rather than climate.

- **P2L69: The terminology “C balance state” does not carry an immediate clear meaning. Does this refer to the annual balance of net carbon exchange? Clarify what C state refers to and how relates to fluxes versus carbon stocks and over which time frames. What is your definition of C uptake and C storage, and over what time frame?**

  The text has been changed to sign and magnitude of the C balance instead.

- **P2L52: Eddy covariance data can include other types of gases, so good to specify: Eddy covariance measurements of CO2**

  Corrected accordingly.

- **P3L82: Resiliency in which sense? Should clarify right away.**

  We meant the resiliency of the sink. However, this part has been removed, so the objectives are more direct and clear. The resiliency of the sink will just be briefly mentioned and defined in the discussion.

- **P3: Sections of the end of the introduction are too detailed to be placed in the introduction and should be moved to the materials and methods section. Please separate material between L82-91 into intro vs methods as appropriate**

  Following your suggestion, we have moved the second part of this paragraph into section 2.2 (Measurements) (L106-110).

- **P3L116: clarify what 5+5 min means**

  The computer running these automatic measurements activates the chambers in succession for 10 minutes. During the first 3 minutes the chamber is open for ventilation, then closed for 5 minutes, and opened again for the last 2 minutes. Each chamber is therefore activated once per cycle while the inactive chambers remain open.

  In the text we have updated *“in succession for 10 min every hour”* (L117)

- **P3L120: spell out km if used in this sentence**

  Corrected accordingly.

- **P5L184: Please clarify what is meant by “sums the variable’s importance up to 1”. This sentence could be clearer**

  We changed the sentence to: “This version of Random Forest sums the relative importance of each variable from 0% up to 100 %, which correspond to the fraction of decision in which a variable is involved to cluster the data.” (L186-187)

- **P5L198: Check grammar: “also exposed a larger variability”**

Corrected: “also exhibited larger variability”.

- **P6L205: what is a non-lap year?**

  Typo, we meant non-leap year. Now corrected.

- **P6L216: measurement period**

  Agreed, changed accordingly.

- **P6L223 & Fig S4: The largest GPP and Reco were found in wetter and warmer years, but what is the statistical measure to support a “tendency towards larger GPP and Reco during wetter and warmer years“? For example, for Reco, half of warmer/wetter are larger and half are smaller than colder/drier.**

  The referee is right, the Figure S4 (now Figure S3) is not correct as such. It shows the annual and precipitation anomaly of the analyzed years (2008-2015) compared to the 1866-2007 time series. This graph should only include the anomalies within the measurement period (i.e. 2008-2015). Based on Ref#1, we have updated Figure 2b to include annual, cold and warm periods during the measurement period. This new input shows that 2010, 2012 and 2013 were relatively warmer and wetter, and had larger GPP and R_{eco}. Figure S3 has been also updated.

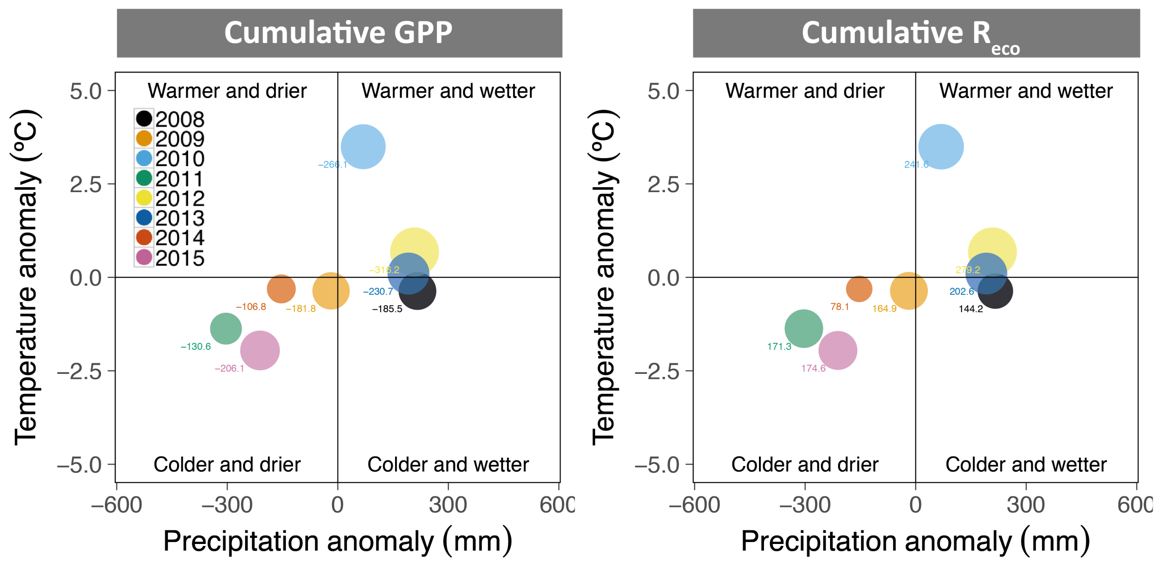

Figure S3: Annual cumulative GPP and R_{eco} defined by annual temperature and precipitation anomalies (2008-2015). The flux size is categorized depending on the flux magnitude (g C m^{-2}), i.e. larger diameters with greater fluxes.

- **P6L228: perhaps be more specific about what the response to the outbreak was in terms of fluxes (not really a response of measurements, but of actual fluxes). Just GPP?**

We have implemented the text to: "coinciding with high NEE and very low GPP (Figure 4)." (L258)

- **P7L281: I wouldn't use "momentarily" to describe hourly data**

  This sentence was changed completely (L286): "*PAR was important at dawn (06 h. WGST) and dusk (15-17 h. WGST), while T_{air} was more important at other times*".

- **P7L285: What is meant by "although Tair appeared to be the less limiting factor". It seems that Tair is the most important variable for Reco, but I'm not sure how it would be limiting or not**

  The referee is correct, the sentence as such sounds odd. We reformulated the text (L285-286): *In terms of CO_2 emission (R_{eco}) the pattern is less clear and noisier, although T_{air} appeared to be the most important variable.*

- **P8L1286: Check grammar in the last sentence. I wouldn't use "catch". Please elaborate on what the connection here is. Why would a decrease in PAR's importance are sense here?**

  We changed "catches" with "revealed". PAR is interesting because it includes information about cloudiness. Negative PAR anomalies in 2011 show less bright growing season compared to the other years, which could have contributed to the C dynamics in the cited year.

- **P8L293: What tendency is that? Also, don't use 'mirror effect'. Use clearer language.**

  The first part of this point has been answer earlier (P6L223 & Fig S4). With respect the mirror effect wording, we updated the text (L337-340*)*:

  > In this study, larger rates of C uptake (GPP) were linked to larger rates of C release (R_{eco}), with the exception of the anomalous year 2011. The relative insensitivity of NEE to meteorological conditions during the snow-free period could be the result of the correlated response of ranked cumulative GPP and R_{eco} (Figure 5) (Richardson et al., 2007; Wohlfahrt et al., 2008)

- **P8L298: I'm not sure this sentence is a natural conclusion from your results: "Thus, the effects on C balance of warming from climate change are not straightforward to infer." Would these processes not be predicted by models? If so, then it could be misleading to state that it is difficult to infer. Provide some context from current literature here if in fact current understanding would have missed this.**

  We believe that models would not necessarily predict these results. For example, the results suggest that autotrophic respiration (Ra) and heterotrophic respiration (Rh) respond to climate together to balance GPP changes. But Ra and Rh are different processes operating on different pools, so such convergence is unlikely in models.

We implemented the text, providing some context from literature (L349-353):

> Further, this study agrees with Parmentier et al., (2011) and Lund et al., (2012), who suggested that a longer growing season does not necessarily increase the net carbon uptake. Here a more negative NEE indicated a stronger C sink (i.e.) in 2012 compared to 2010. Parmentier et al., (2011) hypothesized that this behavior is due to site-specific differences, such as meteorology and soil structure, and that changes in the carbon cycle with longer growing seasons will not be uniform around the Arctic. Thus, the effects of climate change on the tundra C balance of are not straightforward to infer.

- **P8L303: a bit redundant with 'growing season' twice**

  Agreed, we took out the first "growing season".

- **P8L314: outbreak of what?**

  We updated the text with "outbreak of autumn and winter moths". (L368)

- **P8L317, L330: check grammar**

  Corrected, previous referee also pointed towards this sentence. Thanks.

- **P8L322: shortest-lasting, longest-lasting**

  Corrected

- **P9L337: This first two sentences are very unclear as written**

  Agreed, we updated the text in a clearer way (L297-299):

  > The NEE gap-filling and subsequent partitioning into GPP and R_{eco} are needed to understand the CO_2 flux responses to the environmental forcing. However, these procedures expose unavoidable uncertainties in the seasonal C budget calculation (Table 2) and partial inconsistencies between approaches (Figure 4).

- **P9 section 4.2: I don't find this analysis of gap filling to be very informative because estimates regarding which method is best are not testable. Why not test the performance of the gap-filling on years where you have good data coverage by creating artificial gaps and testing model performance against real data? I would find that exercise to be much more compelling and would help you determine which method to apply in years where data is really missing.**

  Quantifying the uncertainty introduced by measurement gaps is difficult. One possibility would be a sensitivity analysis of time series with artificially introduced gaps as the referee suggest. But the choice of gap length and position is difficult, and would render the uncertainty assessment itself quite uncertain. We think the paper already contains a lot of information and this extra analysis would broaden its scope still further. So the best way to give the reader an idea about why we decided to use the auto-chamber (AC) data is that the MDS gap-filling alone introduced NEE values out of range. Instead of blindly trust a gap-filling script, which create odd numbers, we decreased the gap length introducing AC data. We understand AC data incorporated uncertainties to the calculations, although they have been included in the total uncertainty estimation.

We incorporated this discussion into the manuscript (L304-312):

> Quantifying the uncertainty introduced by measurement gaps is complex (Falge et al., 2001; Moffat et al., 2007; Papale et al., 2006). One possibility would be a sensitivity analysis of time series with artificially introduced gaps (Dragomir et al., 2012; Pirk et al., 2017). But the choice of gap length and position is difficult, and would render uncertainty to the uncertainty assessment itself. Instead, we used the EC prediction based on independent auto-chamber (AC) measurements between 2010 and 2013. The agreement between EC and AC were always $R^2 > 0.72$ and $p < 0.001$, and the 95% confidence interval of the predictions were reported together with the resulting uncertainties (Table 2). Although the AC data itself incorporated a new source of uncertainty to the calculations, we consider this method to be less weak than an unreliable gap-filling estimate. We used the AC as platform to decrease the gap length and the total random uncertainty (Aurela et al., 2002) before the MDS algorithm was applied. AC was used together with MDS, and never was used as an independent gap-filling procedure.

- **P9L365: How was the filtering done? This is not clear.**

  We separated the dataset in 3 subgroups: all day data (0-24hr), daytime data (11-14hr) [when GPP is the strongest and will represent the largest part of NEE], and nighttime data (00-03hr) [when NEE=R_{eco}]. By doing this, we make sure that the Random Forest approach will not include bias from the partitioning analysis.

- **P10: I would avoid using 'interesting' so much as a way to describe your observations. It would be more informative to put in context with extant literature. You should not just repeat results here that are listed elsewhere, but put into context. For example, this is done in the latter half of the L380-387 paragraph, but not the first part. The first half of the conclusion is a bit repetitive as well - should not be a repetition of abstract, should be more general.**

  Two 'interesting' words have been removed from the text.

  Following the referee's guideliness, we have worked in the discussion section, not only in the cited areas, but also across the previous subsections.

  Moreover, the conclusion part was reduced to put the key findings in a more general context, omitting detailed values and information that has been addressed previously in the results and discussion sections (L428-435):

We have analyzed eight snow-free periods in eight consecutive years in a West Greenland tundra (64° N) focusing on the net ecosystem exchange (NEE) of CO_2 and its photosynthetic inputs (GPP) and respiration outputs (R_{eco}). Here, the NEE gap-filling exposed inherent uncertainties in the seasonal C budget calculation, but there were also inconsistencies between the flux partitioning approaches used. We find that Kobbefjord acted as a consistent sink of CO_2, during the years 2008-2015, except 2011 that was associated with a major pest outbreak. The results do not show a marked meteorological effect on the net C uptake. However, the relative insensitivity of NEE during the snow-free period was driven by the correlated, balancing responses of GPP and R_{eco}, both more variable than NEE and sensitive to temperature and insolation. In this paper we show a tendency towards larger GPP and R_{eco} during wetter and warmer years. The anomalous year 2011, affected by a biological disturbance, constituted a relatively strong source for CO_2 and reduced GPP more strongly than R_{eco}. A novel analysis assessing the changes of environmental forcing across diurnal, seasonal and annual time scales unmasked patterns of functional responses to C fluxes.

- **Table S1: Avoid using N◦**

  Corrected.

- **Where is Figure S1?**

  The indexing in the supplementary material has been changed to Equations S1, Figures S1, S2, S3 and S4, Tables S1 and S2.

Interactive comment on Biogeosciences Discuss., doi:10.5194/bg-2016-506, 2016.

Exchange of CO_2 in Arctic tundra: impacts of meteorological variations and biological disturbance

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Abstract. An improvement in our process-based understanding of carbon (C) exchange in the Arctic, and its climate sensitivity, is critically needed for understanding the response of tundra ecosystems to a changing climate. In this context, we analyzed the net ecosystem exchange (NEE) of CO_2 in West Greenland tundra (64° N) across eight snow-free periods in eight consecutive years, and characterized the key processes of net ecosystem exchange, and its two main modulating components: gross primary production (GPP) and ecosystem respiration (R_{eco}). Overall, the ecosystem acted as a consistent sink of CO_2, accumulating -30 g C m^{-2} on average (range -17 to -41 g C m^{-2}) during the years 2008-2015, except 2011 (source of 41 g C m-2) that was associated with a major pest outbreak. The results do not reveal a marked meteorological effect on the net CO_2 uptake despite the high inter-annual variability in the timing of snowmelt, and start and duration of the growing season. The ranges in annual GPP (-182 to -316 g C m^{-2}) and R_{eco} (144 to 279 g C m^{-2}) were >5 fold larger than the range in NEE. Gross fluxes and they were also more variable (Coefficients of variation are 3.6 and 4.1 % respectively) than for NEE (0.7 %). GPP and R_{eco} were sensitive to insolation and temperaturestemperature; and there was a tendency towards larger GPP and R_{eco} during warmer and wetter years. The relative lack of sensitivity of NEE to climatemeteorology was a result of the correlated meteorological response of GPP and R_{eco}. During the snow-free season of the 2011 anomalous year of 2011, the studied ecosystem released 41 g C m^{-2} asa biological disturbance related to a larvae outbreak reduced GPP more strongly than R_{eco}. With continued warming temperaturestemperatures and longer growing seasons, tundra systems will increase rates of C cycling. However, although shifts in sink strength will likely be triggered by factors such as biological disturbances, events that will challenge the our forecasting of upcoming C states.

1 Introduction

Quantifying the climate sensitivity of carbon (C) ~~dynamics~~ stocks of the terrestrial biosphere is a major ~~concern~~ challenge for ~~earth~~Earth system science (Williams et al., 2005). In the Arctic, organic soil C storage has ~~has received increased attention in recent years due to large~~ the potential for very large ~~carbon~~ C releases following thaw (Koven et al., 2011) that could create a positive feedback on climate change and accelerate the rate of global warming. Recent reviews have estimated the Arctic terrestrial C pool to be 1400-1850 Pg C, ~~accounting for~~ more than twice the size of the atmospheric C pool (Hugelius et al., 2014; McGuire et al., 2009; Tarnocai et al., 2009) and approximately 50% of the global soil organic C pool (AMAP, 2011; McGuire et al., 2009). Further, Arctic ecosystems have experienced an intensified warming tendency, reaching almost twice the global average (ACIA, 2005; AMAP, 2011; Callaghan et al., 2012c; Serreze and Barry, 2011). The projected Arctic warming is also expected to be more pronounced in coming years (AMAP, 2011; Callaghan et al., 2012a; Christensen et al., 2007; Grøndahl et al., 2008; Meltofte et al., 2008) and ~~temperatures~~temperature, precipitation and growing season length will likely increase in the Arctic (ACIA, 2005; Christensen et al., 2007; Christensen et al., 2004; IPCC, 2007). Given this situation, an improvement in our process-based understanding of CO_2 ~~exchanges~~exchanges in the Arctic, and their climate sensitivity, is critical (McGuire et al., 2009).

~~Understanding~~Measuring the inter-annual C exchange variability in the Arctic tundra is challenging due to extreme conditions ~~through much of the growing season,~~ and the patchy nature of the landscape linked to micro-topography. Different eco-types ~~present~~are linked to different C exchange rates (Bubier et al., 2003)~~, and because the composition of vegetation varies as a response to environmental changes (Glenn et al., 2006), C exchange presents correlated responses~~. Synthesis studies have found a significant spatial variability in NEE (Lafleur et al., 2012; Mbufong et al., 2014) between different tundra sites ~~in the Arctic tundra~~ (Lindroth et al., 2007; Lund et al., 2010) ~~but~~and also ~~a~~ large temporal variability within sites (Aurela et al., 2004; Aurela et al., 2007; Christensen et al., 2012; Grøndahl et al., 2008; Lafleur et al., 2012). Minor variations in the key process of photosynthesis (gross primary production, GPP) and ecosystem respiration (R_{eco}) may promote important changes in the sign and magnitude of the C balance (Arndal et al., 2009; Elberling et al., 2008; IPCC, 2007; Lund et al., 2010; Tagesson et al., 2012; Williams et al., 2000). With continued warming temperature and longer growing seasons, tundra systems will likely have enhanced GPP and R_{eco} rates, but long-term data to investigate and quantify these responses is rare. Further, the effects on net CO_2 sequestration are not known, and may be altered by long-term processes such as vegetation shifts and short-term disturbances like insect pest outbreaks, complicating the prognostic forecast of upcoming C states (Callaghan et al., 2012b; McGuire et al., 2012). Consequently, there is a need to understand how C cycle behaves over time scales from days to years, and the links to environmental drivers. There is a lack of reference sites in the Arctic from where full measurement-based data are available, documenting carbon fluxes at the terrestrial catchment scales. Here we investigate the functional responses of C exchange to environmental characteristics across eight snow-free periods in eight consecutive years in West Greenland.

In recent decades, eddy covariance has become a fundamental method for carbon flux measurements ~~on a~~at the landscape scale (Lasslop et al., 2012; Lund et al., 2012; Reichstein et al., 2005). Eddy covariance ~~data~~measurements of land-atmosphere fluxes, or ~~of CO_2,~~ Net Ecosystem Exchange ~~of CO_2~~ (NEE), of CO_2 can be gap-filled and subsequently separated into ~~its~~ the modulating components ~~Gross Primary Production (~~of GPP~~)~~ and ~~Ecosystem Respiration (~~R_{eco}~~)~~ using flux partitioning algorithms (Reichstein et al., 2005). Th~~o~~ese techniques are critical ~~to~~ for providing~~e~~ a better understanding of the C uptake versus C release behaviour (Lund et al., 2010); but they also allow for an examination of the environmental effects on ecological processes (Hanis et al., 2015). However, large gaps in the measured fluxes may introduce significant uncertainties in the C ~~budgets~~budget estimations. Moreover, GPP and R_{eco} estimates can be calculated in different ways. Some algorithms fit ~~a~~an instantaneous temperature-respiration curve to night-time data to calculate R_{eco} and estimate GPP (Lasslop et al., 2012; Reichstein et al., 2005); others calculate R_{eco} from a light-response curve (Gilmanov et al., 2003;

Lindroth et al., 2007; Lund et al., 2012; Mbufong et al., 2014; Runkle et al., 2013). Unfortunately, different interpretations of the flux gap-filling and partitioning lead to different estimates of NEE, GPP and R_{eco}, as well as undefined uncertainties. ~~Understanding the inter-annual C exchange variability in the Arctic tundra is challenging due to extreme conditions through much of the growing season, and the patchy nature of the landscape linked to micro-topography. Different eco-types present different C exchange rates (Bubier et al., 2003), and because the composition of vegetation varies as a response to environmental changes (Glenn et al., 2006), C exchange presents correlated responses. Synthesis studies have found a significant spatial variability in NEE (Lafleur et al., 2012; Mbufong et al., 2014) between different sites in the Arctic tundra (Lindroth et al., 2007; Lund et al., 2010) but also a large temporal variability within sites (Aurela et al., 2004; Aurela et al., 2007; Christensen et al., 2012; Grøndahl et al., 2008; Lafleur et al., 2012). Minor variations in GPP and R_{eco} may promote changes in the C balance state~~ (Arndal et al., 2009; Elberling et al., 2008; IPCC, 2007; Lund et al., 2010; Tagesson et al., 2012; Williams et al., 2000)~~. With continued warming temperatures and longer growing seasons, tundra systems will likely have enhanced GPP and R_{eco} rates, but long-term data to investigate these responses is rare. Further, the effects on net CO_2 sequestration are not known, and may be altered by long-term processes such as vegetation shifts and short-term disturbances like insect pest outbreaks, complicating the prognostic forecast of upcoming C states (Callaghan et al., 2012b; McGuire et al., 2012). Consequently, there is a need to understand how C cycle behaves over time scales from days to years, and the links to environmental drivers. There is a lack of reference sites from where full measurement-based data is available, documenting the basic carbon stocks and fluxes at the terrestrial catchment scales. Here we investigate the functional responses of C exchange to environmental characteristics across eight snow-free periods in eight consecutive years in West Greenland.~~

The main objectives of this paper are (1) to explore the uncertainties in NEE gap-filling and partitioning obtained from different approaches, (2) to determine how C uptake and C storage respond to the meteorological variability, and ~~assess the resiliency of the studied ecosystem to meteorological variability, and~~ (3) to identify how the environmental forcing affects not only the inter~~-~~-annual~~-~~ variability, but also the hourly, daily, weekly and monthly variability of NEE, GPP and R_{eco}. The intention of this paper is to elaborate on the information gathered in an existing catchment area under an extensive cross-disciplinary ecological monitoring program in low Arctic West Greenland, established under the auspices of the Greenland Ecosystem Monitoring (GEM) (http://www.g-e-m.dk). Using a long-term (8 years) dataset to explore uncertainties in NEE gap-filling and partitioning methods and to characterise the inter-annual variability of C exchange in relation to driving factors can provide a novel input into our understanding of land-atmosphere CO_2 exchange in Arctic regions. Our overarching hypothesis was that both GPP and R_{eco} would respond positively to warmer and longer growing seasons; but, that NEE response to warming would be more complex and variable (positive or negative), depending on subtle balances between plant and microbial climate sensitivity.~~The time series is focused on the snow-free period, our measurements typically start around the end of the snow melt (ca. May-June) and extend until the freeze-in period (between September-October). Once the snow melts, the growing season (i.e. the part of the year when the weather conditions allow plant growth) has been reported as the most relevant period defining both spatial (Lund et al., 2010; Mbufong et al., 2014) and temporal~~ (Aurela et al., 2004; Groendahl et al., 2007; Lund et al., 2012)~~ CO_2 variability.~~

2 Materials and methods

2.1 Site description

~~The field~~Field measurements were conducted in the low Arctic Kobbefjord drainage basin, South-western Greenland (64° 07' N; 51° 21' W) (Figure 1a). The study area is ~~placed~~ located ~~ca.~~ ~20 km SE of Nuuk, the Greenlandic capital. Kobbefjord has been subject to extensive environmental research activities (the Nuuk Ecological Research Operations) since 2007 (http://www.nuuk-basic.dk). The lowland site is located 500 meters from the South-eastern shore of the bottom of

Kangerluarsunnguaq Fjord (Kobbefjord), and 500 meters from the Western shore of the 0.7 km^2 ~~great~~ lake called "Badesø" (Figure 1b). Three glaciated mountains, all above 1000 m. asl., surround the site. The landscape consists on a fen area surrounded by heath, copse and bedrock. The current fen vegetation is dominated by *Scirpus caespitosus*, whereas the surroundings are dominated by heath species such as *Empetrum nigrum*, *Vaccinium uliginosum*, *Salix glauca* and copse species such as *S. glauca* and *Eriophorum angustifolium* (Bay et al., 2008). ~~Kobbefjord belongs to the "Arctic shrub Tundra" according to Skip Walker's BioClimate classification (CAVM Team, 2003) based on the summer warmth index (SWI). In 2010 and 2012 this area went out of the Arctic zone as most of the other SW-Greenlandic locations.~~Kobbefjord belongs to the "Arctic Shrub Tundra" (bioclimate zone E) according to The Circumpolar Arctic Vegetation Map (CAVM Team, 2003; Walker et al., 2005). This map is based on the summer warmth index (SWI), which is the sum of the monthly mean temperature above 0 °C from May to September and the southernmost bioclimatic zone E has the limits 20-35. In 2010 and 2012, ~~climate~~the weather conditions led the area to experience temperatures from warmer climatic zones (SWI ca. 36 and 35 respectively). For the 1961-1990 period, the mean annual air temperature was -1.4 °C and the annual precipitation was 750 mm (Cappelen, 2013). The sun light hours between May and September range from 14 to 21 hours. Outcalt's frost number (Nelson and Outcalt, 1987) indicates that discontinuous permafrost should be present, although no permafrost has been found. Nonetheless, thin lenses of ice may remain until late summer.

2.2 Measurements

We have used eddy covariance (EC) data on NEE, measured during the snow-free period from 2008 to 2015. ~~Our~~ M~~m~~easurements typically started around the end of the snowmelt (ca. May-June) and extended until the freeze-in period (between September-October). Once the snow melts, the growing season (i.e. the part of the year when the weather conditions allow plant growth) has been reported as the most relevant period defining both spatial (Lund et al., 2010; Mbufong et al., 2014) and temporal (Aurela et al., 2004; Groendahl et al., 2007; Lund et al., 2012) CO_2 variability. The EC measurements were conducted in the EddyFen station (Figure 1b and 1c), located in a wet lowland, 40 m. asl. The EC tower is equipped with a closed-path infrared CO_2 and H_2O gas analyzer LI-7000 (LI-COR Inc, USA) and a 3D sonic anemometer Gill R3-50 (Gill Instruments Ltd, UK). The anemometer was installed at a height of 2.2 m, while the air intake was attached 2.0 m above terrain on the steel stand. Adjacent to the EddyFen station, an independent system (Figure 1b and 1c) measures round-the-clock net CO_2 fluxes ~~from soils by~~using an automatic chamber (AC) method based on Goulden and Crill (1997). The transparent chambers, each covering a known surface area of 60 cm by 60 cm, with a height of 30 cm, can be opened and closed ~~sequentially~~by the computer in succession for ~~5+5~~10 min every hour. When the chamber closes, a CO_2 analyzer (SBA-4, PP Systems, UK) monitors both the CO_2 concentration by a close loop of tubing (further information about the set up can be found in Mastepanov et al. (2012). Nearly 20 m from the EddyFen station, the automated SoilFen (Figure 1b and 1c) station provides environmental variables such as air and surface temperature (Vaisala HMP45C), soil temperature at different depths (Campbell scientific 10ST) and relative humidity (Vaisala HMP45C). Two ~~km~~kilometres from these stations, an automatic weather station provides complementary ancillary data such as short & long wave radiation (with a CNR1 instrument), photosynthetic active radiation (with a Kipp & Zonen PAR Lite instrument), precipitation (using an Ott Pluvio instrument) and snow depth (with a Campbell Scientific SR 50). The water table depth data has been monitored using a piezometer located next to each of the six auto chambers. Finally, a robust daily estimate of the timing of snowmelt was analyzed at a pixel level from a time-lapse camera (HP e427) located at 500 m. asl. (Westergaard-Nielsen et al., 2013).

2.3 Data handling

2.3.1 Data collection and pre-processing

Data collection from the EddyFen station was performed using Edisol software (Moncrieff et al., 1997). Raw data files were processed using EdiRe software (version 1.5.0.32, R. ~~Robert~~Clement, University of Edinburgh ~~Clement, University of~~

~~Edinburgh~~) calculating the CO_2 fluxes on a half hourly basis. The flux processing integrated despiking (Højstrup, 1993), 2D rotation, time lag removal by covariance optimization, block averaging, frequency response correction (Moore, 1986) and Webb-Pearman-Leuning correction (Webb et al., 1980). For more information, see Westergaard-Nielsen et al. (2013). Ancillary data (air temperature, soil temperature, incoming short wave radiation, relative humidity, PAR and precipitation) have been temporally resampled using R (https://www.r-project.org/). Time-series-related packages such as *zoo* (Zeileis and Grothendieck, 2005), *xts* (Ryan and Ulrich, 2014) and *lubridate* (Grolemund and Wickham, 2011) were used to get the ancillary data aligned with the flux data in half-hourly basis.

2.3.2 Generating robust and complete flux time series

Before the CO_2 flux time series were analysed, we applied three different processing techniques (u*filtering, gap-filling and partitioning) ~~were applied~~ to (1) filter the NEE data for quality, (2) fill the NEE gaps and (3) separate NEE into GPP and R_{eco}. The identification of periods with insufficient turbulence conditions (indicated by low friction velocity u*) is important to avoid biases and uncertainties in EC fluxes. To control the data quality, ~~here~~ the u* thresholds were bootstrapped by identifying conditions with inadequate wind turbulence according to the method described in (Papale et al., 2006)~~ and the implementation in Papale et al., (In prep.).~~. ~~The data wer~~We sub~~-~~setted the data to similar environmental conditions, aside from friction velocity: 8 years and 7 temperature classes. Within each year/temperature ~~subclass~~ subset the u* threshold (5%, 50% and 95% of bootstrap) was estimated in 1000 samples per year. We used t~~T~~he subsequent gap-filling and partitioning ~~were then applied~~ ~~using~~ based on th~~e~~o~~se different ~~thresholds~~ subsets to propagate the uncertainty of u* threshold estimation across NEE, GPP and R_{eco}.

~~The~~ Our gap-filling ~~was performed with~~ method was~~s~~ similar to Falge et al. (2001), using the marginal distribution sampling (MDS) algorithm, re-adapted from Reichstein et al. (2005) in REddyProc (Reichstein and Moffat, 2014). MDS takes into account similar meteorological data available with different window sizes (Moffat et al., 2007). Parallel to this approach, we also gap-filled the original EC NEE data ~~was also gap-filled~~ with an independent AC NEE dataset (2010-2013). AC data were collected simultaneously with EC data, and so we can ~~be~~ used them ~~to~~ as a cross check. The EC NEE was predicted from AC NEE based on linear regression models. The subsequent product was gap-filled using the MDS algorithm (REddyProc).

~~The~~ We separat~~ed~~tion ~~of~~ NEE into its two main components (GPP and R_{eco}) ~~was achieved applying~~using two approaches: (1) the REddyProc partitioning tool (Reichstein and Moffat, 2014) and (2) a light response curve (LRC) approach (Lindroth et al., 2007; Lund et al., 2012). A brief description of each flux partitioning method is provided in the s~~S~~upplementary material ~~S1.~~(Equations S1). After the flux partitioning comparison, we used ReddyProc-based GPP and R_{eco} estimates on further analyses.

2.3.3 Flux uncertainties

In order to estimate the NEE gap-filling uncertainty, we assessed three different sources of uncertainty~~ were assessed~~. First, we addressed the 95% confidence interval of the EC prediction based on AC data. Second, we inferred the random uncertainty of filled half-hourly values~~ was inferred~~ by the spread of variable with otherwise very similar environmental conditions. REddyProc uses the gap-filling to estimate an observation uncertainty also for the measured NEE, by temporarily introducing artificial gaps (T. Wutzler and M. Migliavacca (BGC-Jena), personal communication). Finally, we assessed the effect of~~the~~ ~~uncertai~~uncertainty in ~~n~~ the ~~-~~estimate of the u* threshold~~ was addressed~~. In the u*-NEE relationship we want to exclude the probably false low fluxes (absolute NEE values) ~~with~~ at low u*. When choosing a lower u* threshold, ~~also~~ the associated lower flux will contribute to the gap-filling and the annual sums. Therefore, there is a tendency of a lower absolute NEE associated with lower u*. The difference between the 5% and 95% of bootstrap provides a means of the uncertainties based on the u* filters. ~~All these sources of uncertainties~~ We~~were~~ summed and propagated all these sources of uncertainties over time. ~~Moreover, t~~The GPP and R_{eco} uncertainties include the bias from the one-to-one flux comparison obtained from each model. The micrometeorological sign convection used in this study present uptake fluxes (GPP) as negative, while the released fluxes (R_{eco}) are shown as positive.

2.4 Identifying environmental forcing

Snow- and ~~phenological~~phenology- related variables such as end of the snowmelt period~~,~~ and the start, end and length of the growing season are important components shaping the ~~arctic~~Arctic CO_2 dynamics. In this study we defined the end of the snowmelt period as the day of year when ~~less~~ more than ~~2~~80% of the surface of the fen was considered snow-~~-~~free; the threshold was chosen in agreement with suggestions previously reported in Hinkler et al. (2002) and Westergaard-Nielsen et al. (2015). For the start, end and length of the growing season (GS_{start}, GS_{end}, GS_{length}); the GS_{start} and the GS_{end} were defined as the first and last day when the consecutive 3-~~days~~day NEE average was negative (i.e. CO_2 uptake) and positive (i.e. CO_2 release) respectively (Aurela et al., 2004), while GS_{length} is the number of days between GS_{start} and GS_{end}).

A Random Forest machine-learning algorithm (Breiman, 2001; Pedregosa et al., 2011) was utilized in a data-mining exercise to identify how the environmental controls affect the variability of NEE, GPP and R_{eco}. Random forest calculates the relative importance of explanatory variables over the response variables. Here, we use photosynthetic active radiation (PAR), air ~~temperatures~~temperature (T_{air}), precipitation (Prec) and vapor pressure deficit (VPD) to explain the response of C fluxes (NEE, GPP and R_{eco}) to climate variability. Each decision tree in the forest is trained on different random subset of the same training dataset. The ~~code~~Random Forest is ~~able to group~~a classifier that groups explanatory variables and, in each final cluster, a multiple linear regression is built to reproduce fluxes as function of driving factors. This approach has been used to ~~analyze NEE exchange for an Australian flux tower (Hinko-Najera et al., 2016) or~~ extrapolate maps of biomass (Baccini et al., 2012; Exbrayat and Williams, 2015). This version of Random Forest sums the ~~variable's~~relative importance of each variable from 0% up to ~~1 (i.e. the relative influence) that~~100 %, which correspond to the fraction of decision in which a variable is involved to cluster the data. We applied Random Forest to assess the relative importance of PAR, T_{air}, Prec and VPD at different temporal scales (hourly, daily, weekly and monthly), aggregating them at the time scale indicated and lumping all the years together. (Table S1; supplementary material). Moreover, we also evaluated the diurnal, seasonal and annual pattern for each explanatory variable (data binned per hour, this is one Random Forest per hour of the day, day of the year and year respectively). To make sure that these results were not an artefact of the partitioning method that is based on a relationship between hourly R_{eco} and T_{air}, we performed the same analyses using day-time and night-time only hourly NEE as respective proxies for GPP and R_{eco}. Based on these results (Table S2;~~,~~ supplementary material) we concluded that the approach was robust for the Kobbefjord site.

3 Results

3.1 Inter-annual and seasonal variation of environmental and phenological variables

The annual mean ~~temperatures~~temperature documented from Nuuk (-0.5 °C)~~, together with the measured in~~ and Kobbefjord (-0.4 °C)~~,~~ in the 2008-2015 period were generally warmer compared to the long time series between 1866 and 2007 ~~((~~(Cappelen (2016); Figure ~~S2~~S1; supplementary material), with an annual ~~temperatures~~temperature average of -1.5 °C ~~(Figure 2)~~. The 2008-2015 period ~~temperatures~~temperature also ~~exposed a~~exhibited larger variability (Coefficients of variation (CV) = 283.3 %) compared to the 1866-2007 period (CV = 79.3 %). The 2008-2015 mean annual temperature measured in Kobbefjord fluctuated between -1.7 °C in 2011 and 3.4 °C in 2010. Moreover, the mean annual ~~mean precipitations~~precipitation documented from the nearby station of Nuuk (885 mm~~), but also~~) and the one measured across the eight years study in Kobbefjord (862 mm~~),~~) were ~~predominantly~~both significantly higher than the 1931-2007 mean (689 mm), although less variable (CV~~=~~ = 30.8 % and 24.5 % respectively). Overall, 2008, 2009, 2010, 2012, 2013 and 2014 have shown warmer and wetter anomalies while 2011 and 2015 presented colder and drier anomalies compared to the long-term mean (Figure ~~2).~~ 2a). Among the eight study years (figure 2b), the temperature and precipitation anomalies in the warm season (June to September) ranged from about -1°C (2011, 2013 and 2015) to +1.5°C (2010) and -96 mm (2011) to about +125 mm (2012 and 2013), respectively. The cold season (October to May) anomalies have shown greater variability compared to the warm season, and 2010, 2012 and 2013 experienced warmer and wetter winters, while 2011 and 2015 were colder and drier.

The end of the snowmelt period and the growing season start/length presented high inter-annual variability (CV ~~are~~ were 9.5, 9.0 and 19.0 %, respectively). Kobbefjord became snow~~-~~-free in DOY 154 (June 3rd for non-~~lap~~leap years, SD=15) on average. On average, the site switched from being a source of CO_2 to a sink (GS_{start}) on DOY 175 (June 24th, SD=20), and remained so (GS_{end}) until DOY 241 (July 29th, SD=8.4)(Table 1). The GS_{start} and the GS_{length} did not follow a consistent pattern among the analysed years, the growing season timing have fluctuated substantially. The high inter-annual variability of the GS_{start} correlated with variations in temperature, end of ~~snow melt~~snowmelt period and VPD ($p<0.05$). Highest variability was observed during 2009-2012. The 2010's GS_{length} was nearly twice as long as to 2011. Indeed, GS_{start} in 2011 differs only by 26 days with the GS_{end} in 2010.

~~3.2~~3.2 Data processing and quality

The NEE gap-filling and subsequent partitioning obtained from different approaches exposed inconsistencies in performance and specific uncertainties in the seasonal C budget ~~computation~~calculation. During the eight study snow-free periods~~years growing seasons~~, ~~there were~~data gaps made up 46.5 % of ~~missing~~the~~ NEE data~~ record from the EddyFen station, due to unfavourable micro-meteorological conditions, instrument failures, maintenance and calibration (Jensen and Christensen 2014), but also due to the rejection of low quality flux measurements or too low u*. In 2014 a major instrument failure forced the station to stop measurements in the middle of the season. In 2010 and 2012 there were two more interruptions in the measurements (data gaps of >20 days) although the problems could be ~~repaired~~solved before the end of the season. Such prolonged gaps led to unreliable gap-filled NEE estimates. REddyProc marginal distribution sampling (MDS) algorithm tended to fill these large gaps with high peaks of respiration at noon times, coercing C uptake underestimation. For this reason, an independent AC NEE dataset (2010-2013) was tested to gap-fill EC data (Figure 3 and Figure S2; supplementary material). The R^2 obtained from the EC-AC correlations were always > 0.70 (2010: R^2= 0.80, $p < 0.001$; 2011: R^2= 0.72, $p < 0.001$; 2012: R^2= 0.80, $p < 0.001$; 2013: R^2= 0.84, $p < 0.001$). By using AC data, the~~The number of~~ ~~propotion~~proportion of missing data~~ gaps~~ was reduced to 28% and ~~it was~~we found that the random uncertainty from the combination of AC and MDS algorithm decreased 5% on average. By using the u*filtering and the AC data together with EC, there was an increase of ~~ca~~ ~6 % in terms of C sink strength. Moreover, the propagated uncertainty in NEE never exceeded ±1.8 g C m^{-2}, mainly because the error related to u* filtering was low. Further, we hypothesized that different flux partitioning approaches would lead to different estimates of GPP and R_{eco}, however, the results suggest a relatively good agreement (Figure 4). There was a higher degree of agreement with regard to GPP (R^2 = 0.83) compared with R_{eco} (R^2 = 0.30). LRC tended to ~~calculate~~estimate 12 % and 15 % larger GPP and R_{eco}~~-~~, respectively, compared to REddyProc~~, 12 % and 15 %, respectively~~.

3.3 Inter-annual and seasonal variation of CO_2 ecosystem fluxes

Overall, land-atmosphere CO_2 exchange measured ~~between~~ for the snow free periods of 2008~~ and ~~-2015, omitting 2011, acted as a sink of CO_2, taking up -30 g C m^{-2} on average (range -17 to -41 g C m^{-2}) (Figure 5; Table 2). The cumulative NEE showed a characteristic pattern during the ~~measuring~~measurement period (Figure 5), with an initial loss of carbon in early spring right after snowmelt (also observed in Figure 3), followed by an intense C uptake as assimilation exceeded respiratory losses, triggered by increases in temperature, PAR and vegetation growth. This transition point matched the growing season start, when NEE switched from positive values (a net C source) to negative values (a net C sink~~,~~). Eventually, the ecosystem turned again into a net C source, defining the growing season end. Even with high inter-annual variability in terms of the end of snowmelt time and growing season start/length (Table 1), the results do not show a marked meteorological effect on the ~~net C uptake~~NEE. The ranges in annual GPP (-182 to -316 g C m^{-2}) and R_{eco} (144 to 279 g C m^{-2}) (Table 2) were >5 fold larger and more variable (CV are 3.6 and 4.1 % respectively) than for NEE (0.7 %). There was a tendency towards larger GPP and R_{eco} during warmer and wetter ~~and warmer~~ years (Figure ~~S4~~S3~~;~~; supplementary material), but there were no warmer and drier years during the study period. ~~.~~The strongest growing season CO_2 uptake occurred in 2012 (NEE = -74.2 g C m^{-2}; GS_{length} = 78 days), followed by 2010 (NEE = -70.0 g C m^{-2}; GS_{length} = 85 days) (Tables 1 and 2). A lengthening of the growing season did not increase the net carbon uptake in this study. In other words, an earlier end of the snowmelt resulting in a longer growing season length did not lead to a stronger carbon sink.

The anomalous year, 2011, constituted a relatively strong source for CO_2 (41 g C m^{-2}) and was associated with a major pest outbreak, which reduced GPP more strongly than R_{eco}. The larvae of the moth *Eurois occulta* data, collected from pitfall traps in the surrounding *Salix* and *Empetrum* dominated plots, showed a strong peak at the beginning of the 2011 growing season ~~(Lund et al., in press) coinciding with the C loss intensification.~~(Lund et al., 2017) coinciding with high NEE and very low GPP (Figure 4). In 2011 up to 2078 larvae were observed while other years only 14 (2008), 82 (2009), 186 (2010), 0 (2012) and 8 (2013). It is likely that the ~~flux measurements~~reduced primary production in the ~~lowland~~ wetland area ~~were~~ was a partial response to the *Eurois occulta* outbreak.

The daily aggregated NEE-GPP relationships displayed consistent linear correlation (2008-2015: R^2= 0.77, $p < 0.001$) across the assessed years (Figure 6a). The linear correlations were weaker in 2010 and 2011. A hysteresis was detected in 2010 (i.e. long growing season with higher R_{eco} in autumn compared to spring), while strong C releases ~~have been~~was observed in 2011 across June and July. The relation between GPP and R_{eco}, which can be understood as the degree of coupling between inputs and outputs of C, and therefore the degree of C sink strength, ~~has show~~showed~~n~~ non-linear patterns (Figure 6b). The curved behaviour is likely because GPP increased more than R_{eco}~~.~~ during early growing season, except for in 2011. Moreover, R_{eco} lagged behind GPP due to (1) the vegetation green-up in the first part of the growing season and (2) the higher respiration rates due to increased biomass in the second part. The years with clearer hysteresis coincide with the years with positive temperature anomalies (i.e. 2010, 2012 and 2013) of the 2008-2015 series. It is worth mentioning the different direction (clockwise vs counter-clockwise) in the hysteresis observed these years between June, July and August. The data suggest that the clockwise 2012 hysteresis was due to greater gross C cycling (GPP and R_{eco}) in June and July favored by warmer conditions; while in 2010 (counter-clockwise hysteresis), the higher gross C fluxes have been measured in August with warmer and wetter conditions (Figure S4; supplementary material).

~~The strongest growing season CO_2 uptake occurred in 2012~~ (NEE = ~~, leading to a -74.2 g C m^{-2}~~) ~~cumulative NEE, while~~ the ~~weakest occurred in 2011 (NEE = -12.3 g C m^{-2}) it was only -12.3 g C m^{-2} during the weakest growing season in 2011 (Table 2). A lengthening of the growing season (2010 was the year with longest growing season) did not increase the net carbon uptake in this study. In other words, an earlier end of the snowmelt resulting in a longer growing season length did not lead to a stronger carbon sink. The gap-filled NEE time series (Figure 3) show there was predominantly CO_2 uptake between 06 h and 18 h West Greenland Summer Time (WGST). The fingerprints illustrate and emphasize how variable the GS_{start} and the GS_{length} were across the years, but also show the difference in magnitude of the growing season regarding carbon CO_2 uptake.~~

~~**3.3 Data processing and quality**~~

~~**The NEE gap-filling and subsequent partitioning obtained from different approaches exposed inconsistencies in performance and specific uncertainties in the seasonal C budget computation. During the eight study years, there were 46.5 % of missing NEE data from the EddyFen station due to unfavourable micro-meteorological conditions, instrument failures, maintenance and calibration (Jensen and Christensen 2014) but also due to the rejection of fluxes with deficient quality or too low u*. In 2014 a major instrument failure forced the station to stop measurements in the middle of the season. In 2010 and 2012 there were two more interruptions in the measurements (data gaps of >20 days) although the problems could be repaired before the end of the season. Such prolonged gaps led to unreliable gap-filled NEE estimates. REddyProc marginal distribution sampling (MDS) algorithm tended to fill these large gaps with high peaks of respiration at noon times, coercing C uptake underestimation. For this reason, an independent AC NEE dataset (2010-2013) was tested to gap-fill EC data (Figure S3; supplementary material). The R^2 obtained from the EC-AC correlations were always > 0.70 (2010: R^2= 0.80, $p < 0.001$; 2011: R^2= 0.72, $p < 0.001$; 2012: R^2= 0.80, $p < 0.001$; 2013: R^2= 0.84, $p < 0.001$). The number of gaps was reduced by 18.5% and it was found that the random uncertainty from the combination of AC and MDS algorithm decreased 5% on average. By using the u*filtering and the AC data together with EC, there was an increase of ca 6 % in terms of C sink strength. Moreover, the propagated uncertainty in NEE never exceeded ±1.8 g C m^{-2}, mainly because the error related to u* filtering was low. Further, we hypothesized that different flux partitioning approaches would lead to different estimates of GPP and R_{eco}, however, the results suggest a relatively good agreement (Figure 4). There was a higher degree of agreement with regard to GPP compared with R_{eco}. LRC tended to calculate larger GPP and R_{eco} compared to REddyProc, 12 % and 15 %, respectively.**~~

3.4 Environmental forcing

~~The daily aggregated NEE-GPP relationships display consistent linear correlation (2008-2015: R^2= 0.77, $p < 0.001$) across the assessed years (Figure 6a). The linear correlations were weaker in 2010 and 2011. A hysteresis was detected in 2010 (i.e. long growing season with higher R_{eco} in autumn compared to spring), while strong C releases have been observed in 2011 across June and July. The relation between GPP and R_{eco}, which can be understood as the degree of coupling between inputs and outputs, and therefore the residence timedegree of fixed C sink strength, has shown non-linear patterns (Figure 6b). The curved behaviour is likely because GPP increased more than R_{eco}. Moreover, R_{eco} lagged behind GPP due to (1) the vegetation green-up in the first part of the growing season and (2) the higher respiration rates due to increased biomass in the second part. It is worth mentioning the high variability of C sink strength between summer months (June, July and August). The years with clearer hysteresis coincide with the years with positive temperature anomalies (i.e. 2010, 2012 and 2013) of the 2008-2015 series.~~

The varied importance of meteorological variables (such as PAR, T_{air}, VPD and Precipitation) obtained from Random Forest at different temporal scales (hourly, daily, weekly and monthly) ~~revealed~~ showed differences in behaviour depending on the time aggregation utilized (Figure 7). PAR dominated NEE and GPP while T_{air} correlated the most with R_{eco} in hourly averages, whereas T_{air} became increasingly important at longer temporal aggregations for all the fluxes (Figure 7). VPD and precipitation were not ~~found to be~~ as important as the other variables while the use of water table depth in the analysis was discarded due to its very low impact on CO_2 fluxes. In general, NEE and GPP showed similar ~~performances~~distributions of importance, reinforcing the linear relationships found between NEE and GPP (Figure ~~7~~6). The standard deviation of the ~~importance's~~ variables' importance (across 1000 decision trees) tended to increase at coarser time aggregations.

Changes of environmental forcing (PAR, T_{air} and VPD) across diurnal, seasonal and annual time scales reveal patterns of functional responses to C fluxes. The diurnal cycle analyses on hourly data showed the changes in importance between day- and night-time (Figure 8). NEE and GPP had two predominant variables (T_{air} and PAR) determining the variability at day-time. PAR was important~~There was a significant decline of T_{air} importance early in the morning~~at dawn (06 h. WGST) and dusk (20 h. WGST), while T_{air} was more important at other times. This performance indicates a threshold response to PAR, and a more continuous response to temperature~~, coinciding with a peak of PAR at 06 h. WGST, triggering photosynthesis~~

and the C uptake. T_{air} rapidly turnedretu back as a primary driver along through the day. until the range period 15-17 h. WGST, when it momentarily dropped down, again, due to PAR's influence. On the other hand, R_{eco} was mainly driven by T_{air} at both night-time and day-time. VPD and PAR barely had ahad a negligiblen impact on CO_2 releaseR_{eco}. The seasonal pattern importance showed PAR dominating NEE and GPP from early June to early October (Figure 8), while T_{air} and VPD became more important before and after the snow--free conditions. In terms of CO_2 emissionrelease (R_{eco}) the pattern is less clear and noisier, although T_{air} appeared to be the less limiting factor.most important variable. Finally, the annual pattern exposes a performance in line with previous results, i.e. PAR dominated NEE and GPP while R_{eco} was more sensitive to variations of T_{air}. Interestingly, the Random Forest analysis catchesrevealed a decrease of PAR's importance in 2011, same year exposing the sharp decrease of C sink strength.

4 Discussion

4.14.1 Data processing and quality

The NEE gap-filling and subsequent partitioning into GPP and R_{eco} are needed to understand the CO_2 flux responses to the environmental forcing. However, these procedures expose unavoidable uncertainties in the seasonal C budget calculation (Table 2) and partial inconsistencies between approaches (Figure 4) and unavoidable uncertainties in the seasonal C budget calculation (Table 2). In this study, we used a marginal distribution sampling (MDS) gap-filling technique, an enhancement to the standard look up table (LUT). Both methods have shown a good overall performance compared to other procedures such as non-linear techniques (NLRs) or semi-parametric models (SPM), but slightly inferior to artificial neural network (ANN) (Moffat et al., 2007). However, tthe MDS gap-filling alone introduced NEE estimates out of rangehe algorithm has shown a flaw in performance across the two extensive and uninterrupted gaps in 2010 and 2012 (Figure S2; supplementary material). Quantifying the uncertainty introduced by measurement gaps is difficultcomplex- (Falge et al., 2001; Moffat et al., 2007; Papale et al., 2006)(reference). One possibility would be a sensitivity analysis of time series with artificially introduced gaps (Dragomir et al., 2012; Pirk et al., 2017) (reference). But the choice of gap length and position is difficult, and would render uncertainty to the uncertainty assessment moreitself itself quite uncertainuncertain. (reference). Instead, Estimated NEE during these periods were unrealistic and led to marked NEE underestimations (i.e. lower CO2 sink strength).we used –the EC prediction based on independent auto-chamber (AC) measurementsdata auto-chamber (AC) observations in the gap-filling processbetween 2010 and 2013. The agreement between methodsEC and AC were always $R^2 > 0.72$ and $p < 0.001$, and the 95% confidence interval of the predictions were reported together with the resulting uncertainties (Table 2). We understandAlthough the AC data itself incorporated a new source of uncertainty to the calculations, but we also thinkconsider this method to beis less weak sthan an unreliable gap-filling estimate. We used the AC as platform to decrease the gap length- and so the total random uncertainty –(Aurela et al., 2002) –before the MDS algorithm can operatewas applied. AC was used together with MDS, and never was used as an independent gap-filling procedure. We understand the AC data itself incorporated new source of uncertainties to the calculations, but it is less weak than an unreliable gap-filling estimate. Overall, the AC data reduced the gap length and gap-filling uncertainties.

The NEE partitioning obtained from REddyProc and LRC suggests a relatively good agreement in model performance. The one-to-one comparison between different approaches found a better agreement with regard to GPP compared to R_{eco}. LRC GPP was 12 % higher than REddyProc GPP; while LRC R_{eco} was 15 % higher than REddyProc R_{eco}. In this analysis, REddyProc produced smoother R_{eco} estimates compared to the noisier GPP estimates, whereas LRC performed the other way around. This is mainly because measurement noise goes into GPP for REddyProc method, and into R_{eco} for LRC method. REddyProc retrieves positive GPP values whereas LRC method results in negative R_{eco} values. Both scenarios are not fully convincing, although it is not straightforward how they should be treated. By removing all positive GPP / negative

R_{eco} values would risk removing only one side of the extremes. Besides night-time based (REddyProc) and day-time based (LRC) partitioning approaches, several implementations have been proposed to improve the algorithms performance. Lasslop et al. (2010) has modified the hyperbolic LRC to account for the temperature sensitivity of respiration and the VPD limitation of photosynthesis. Further, Runkle et al. (2013) proposed a time-sensitive multi-bulk flux-partitioning model, where the NEE time series was analyzed in one-week increments as the combination of a temperature-dependent R_{eco} flux and a PAR-dependent flux (GPP). However, it remains uncertain under which circumstances each partitioning approach is more appropriate, especially in the boundaries between low- and high-Arctic due to the lack of dark night alongduring polar days (wheren the light is not / is not respectively a a limiting factor for the plant growth). Since there are few methods with an unclear precision, an evaluation study on the effect of using different partitioning approaches along latitudinal gradients would be very beneficial to assess the suitability for each method.

Inter-annual and seasonal variation of CO_2 ecosystem fluxes

The balance between the two major gross fluxes in terrestrial ecosystems, photosynthetic inputs (GPP) and respiration outputs (R_{eco}), has experienced larger temporal variability than NEE (CV are 3.6, 4.1 and 0.7 % for GPP, R_{eco} and NEE, respectively). These results suggest that both GPP and R_{eco} were strongly coupled and sensitive to meteorological conditions such as insolation and temperatures (Figure 7 and 8). Interestingly, the tendency to wetter and warmer conditions led to greater rates of C cycling associated with larger GPP and R_{eco} (Figure S4, supplementary material). The mirror effect observed from the ranked cumulative GPP and R_{eco} (Figure 5) also suggest that the relative insensitivity of NEE to climate could be the result of the correlated response of both GPP and R_{eco}. Further, this study suggests that a longer growing season does not necessarily increase the net carbon uptake (Parmentier et al., 2011), since 2012 presented stronger C sink strengths (i.e. more negative NEE) than 2010. Thus, the effects on C balance of warming from climate change are not straightforward to infer.

NEE exchange4.2 Inter-annual and seasonal variation of CO_2 ecosystem fluxes

The balance between the two major gross fluxes in terrestrial ecosystems, photosynthetic inputs (GPP) and respiration outputs (R_{eco}), has experienceddisplayed larger temporal variability than did NEE. These results suggest that both GPP and R_{eco} were strongly coupled and sensitive to meteorological conditions such as insolation and temperature (Figure 7 and 8). InterestinglyInterestingly, the tendency to warmer and wetter and warmer conditions led to greater rates of C cycling associated with larger GPP and R_{eco} (Figure S3; supplementary material). This result does not entirely coincide with Peichl et al. (2014), even though they performed a similar analysis for a Swedish boreal fen. This finding points towards the complexity in the response of wetland ecosystems towards changing environmental conditions. The response is dependent on many things, such as hydrological settings, and these differ between sites. Peichl et al. (2014) In this study, larger rates of C uptake (GPP) were linked to larger rates of C release (R_{eco}), with the exception of the anomalous year 2011. Figure 5 suggests that The results suggest that ttThe relative insensitivity of NEE to meteorological conditions during the snow-free period could be the result of the correlated response of ranked cumulative GPP and R_{eco} (Figure 5) (Richardson et al., 2007; Wohlfahrt et al., 2008) (Figure 5).

This site likely receives more precipitation relative to many other tundra ecosystems, and has no permafrost, thus the NEE response to climate could be less variable. However, as Kobbefjord is located in a costalcoastal area, so it is not surprising to receive high precipitation, and other ecosystems such as coastal blanket bogs (Lund et al., 2015) often receive even more precipitation, without a clear impact of drought effect on the NEE sensitivity (Lund et al., 2015). On the other handhandFurthermore, permafrost adds another layer of complexity to the C dynamics (Christensen et al., 2004; Koven et al., 2011; Schuur et al., 2015)(Åkerman and Johansson, 2008; Christensen et al., 2004; Johansson et al., 2013; Koven et al., 2011; Romanovsky et al., 2010; Schuur et al., 2015). Although some studies showed similarities of CO_2 fluxes in various northern wetland ecosystems with and without permafrost (Lund et al., 2015), permafrost has strong influence on the hydrology of peatlands (Åkerman and Johansson, 2008), and therefore their topography and distribution of vegetation (Johansson et al., 2013). Especially in the context of climate warming permafrost thaw can cause large changes to the ecosystems. Further, this study agrees with Parmentier et al. (2011) and Lund et al. (2012),~~-~~ who suggested that a longer growing season does not necessarily increase the net carbon uptake. Here a more negative NEE indicated a stronger C sink (i.e.) in 2012 compared to 2010. Parmentier et al. (2011) hypothesized that this behavior is due to site-specific differences, such as meteorology and soil structure, and that changes in the carbon cycle with longer growing seasons will not be uniform around the Arctic. Thus, the effects of climate change on the tundra C balance of are not straightforward to infer.

NEE measured in Kobbefjord from 2008 to 2015 indicates a consistent sink of CO_2 (within a range of -17 to -41 g C m^{-2}) with exception of the year 2011 (+41 g C m^{-2}) (Table 2). The year 2011, associated with a major pest outbreak, reduced GPP more strongly than R_{eco} (Figure 5) and Kobbefjord turned into a strong ~~growing season~~ C source within an episodic single growing season. The return to a substantial cumulative CO_2 sink rates following the extreme year of 2011 shows the ability of the ecosystem to recover from the disturbance (Lund et al., 2017). Indeed, the ecosystem not only shifted back from being a C source to a C sink, but it also changed rapidly from one year to the next. Thus we found ~~evidences~~evidence in Kobbefjord of ecosystem resilience to the meteorological variability, similar to other cases described in other northern sites (Peichl et al., 2014; Zona et al., 2014). Only a few ~~references~~reference sites have reported similar decreases in net C uptake, but in no case as large as the one observed here. Zona et al. (2014) described an effect of delayed responses to an unusual warm summer in Alaska. Their results suggested that vascular plants, which have enhanced their physiological activity during the warmer summer, might have difficulties readapting to cooler, but not atypical, conditions, which have provoked a significant decrease of GPP and R_{eco} the following year. In their study, the ecosystem returned to be a fairly strong C sink after two years, suggesting strong ecosystem resilience. Moreover, Hanis et al. 2015 have reported comparable C sink - C source variations in a Canadian fen within the growing season due to changes in the water table depth. Drier and warmer than normal conditions have triggered an increase in C source strength. Finally, during an extensive outbreak of autumn and winter moths in a subarctic birch forest in Sweden, Heliasz et al. (2011) observed a similar decrease in net sink of C (most likely due to weaker GPP) across the growing season. However, the C source strength (NEE = 40.7 g C m^{-2}) found in 2011 at Kobbefjord was higher compared to these other cases. To our knowledge, ~~(Rocha and Shaver, 2011)it has not been reported~~ such abrupt disturbance concerning C sink strength in Arctic tundra has not be previously reported excluding severely burned landscapes (Rocha and Shaver, 2011).

A combination of different factors could have led to the sharp change in C balance observed between 2010-2011, both physical and biological. ~~The year 2010 had the highest mean annual temperature while 2011 had the lowest, 3.4 °C and -1.7 °C respectively (compared to -0.4 °C, the 2008-2015 mean annual temperature). The warmest winter-time temperature (Dec-Jan-Feb) occurred in 2010, with -2.7 °C (compared to -6.79 °C, the 2008-2015 mean wintertime temperature). These climatic conditions stimulated the thinnest (0.05 m compared to averaged 0.26 m) and short-lasting snow pack in 2010; whereas 2011 had the thickest (0.41 m compared to averaged 0.26 m) and long-lasting snow pack due to the cold summer. Consequently, 2010 experienced the longest growing season (85 days) while 2011 had the shortest (only 47 days) as well as the latest start of the growing season.~~The year 2010 had the warmest mean annual temperature (3.4 °C compared to the -0.4 °C mean annual temperature for 2008-2015~~-mean~~) and the warmest mean wintertime temperature (-2.7 °C compared to the -6.79 °C mean for 2008-2015~~-mean~~) (Figure 2a). These climatic conditions generated the thinnest (maximum daily snow depth of 0.3 m compared to averaged 0.9 m) (Table 1) and shortest-lasting snowpack. Consequently, 2010 had the longest growing season (85 days) and very high growing season C uptake (-70 g C/ m^{-2}). Increases in temperature can lead to high respiration rates during early winter (Commane et al., 2017; Zona et al., 2016), but also during the following summer (Helfter et al., 2015; Lund et al., 2012)~~(Helfter et al., 2015)~~, which is related to soil temperature and snow dynamics. Further, in Kobbefjord the year 2011 had one of the lowest mean annual temperatures and mean wintertime temperatures (-1.7 and -6.1°C respectively), which created the thickest (maximum daily snow depth of 1.4 m) and the longest-lasting snowpack, leading to the shortest growing season for the study period (only 47 days). According to Lund et al. (2012), below thick snowpack soils will be insulated from reaching low temperature, acting as lid and preventing R_{eco} from being released to the atmosphere until the snowmelt period. ~~Further, PAR appeared to be a limiting factor for NEE in 2011 (Figure 8). All these characteristics together may have triggered an enhanced productivity (i.e. more negative GPP) in 2010 compared to the lowest productivity and C sink strength estimated in 2011 (i.e. least negative GPP and NEE).~~ Finally, larvae of the noctuid moth *Eurois occulta* outbreak occurred in 2011, ~~overlapped~~ overlapping the abrupt decrease of C sink strength observed. Although we cannot provide a quantification of change attributed to meteorological variations and biological disturbances, there ~~are evidences~~is evidence showing that the ~~month~~moth outbreak could partially ~~has~~have decreased the C sink strength in Kobbefjord. In an undisturbed scenario, the meteorological conditions in 2015, colder and dryer than the mean 2008-2015 period (Figure 2), but similar to 2011, would have stimulated similar behaviours in terms of C fluxes. However, the cumulative fluxes in 2015 (Figure 5) followed analogous patterns compared to the rest of the years. This evidence agrees with literature (Callaghan et al., 2012b; Lund et al., ~~in press~~2017) on the fact that tundra systems can fluctuate in sink strength influenced by factors such as episodic disturbances or species shifts, events very difficult to predict.

~~4.2 Data processing and quality~~

~~The NEE gap-filling and subsequent partitioning exposed inconsistencies in performance and specific uncertainties in the seasonal C budget computation. The uncertainties found underlays the strong challenges related to accurate gap-filling and partitioning estimations. In this study, we used a marginal distribution sampling (MDS) gap-filling technique, an enhancement to the standard look up table (LUT). Both methods have shown a good overall performance compared to other procedures such as non-linear techniques (NLRs) or semi-parametric models (SPM), but slightly inferior to artificial neural network (ANN) (Moffat et al., 2007). However, the algorithm has shown a flaw in performance across the two extensive and uninterrupted gaps in 2010 and 2012 (Figure S3, supplementary material). Estimated NEE during these periods were unrealistic and led to marked NEE underestimations (i.e. lower CO_2 sink strength).~~

~~The NEE partitioning obtained from REddyProc and LRC suggests a relatively good agreement in model performance. The one-to-one comparison between different approaches found a better agreement with regard to GPP compared to R_{eco}. LRC GPP was 12 % higher than REddyProc GPP; while LRC R_{eco} was 15 % higher than REddyProc R_{eco}. In this analysis, REddyProc produced smoother R_{eco} estimates compared to the noisier GPP estimates, whereas LRC performed the other way around. This is mainly because measurement noise goes into GPP for REddyProc method, and into R_{eco} for LRC method. REddyProc retrieves positive GPP values whereas LRC method results in negative R_{eco} values. Both scenarios are not fully convincing, although it is not straightforward how they should be treated. By removing all positive GPP / negative R_{eco} values would risk removing only one side of the extremes. Besides night-time based (REddyProc) and day-time based (LRC) partitioning approaches, several implementations have been proposed to improve the algorithms performance. Lasslop et al. (2010) has modified the hyperbolic LRC to account for the temperature sensitivity of respiration and the VPD limitation of photosynthesis. Further, Runkle et al. (2013) proposed a time-sensitive multi-bulk flux-partitioning model, where the NEE time series was analyzed in one-week increments as the combination of a temperature-dependent R_{eco} flux and a PAR-dependent flux (GPP). However, it remains uncertain under which circumstances each partitioning approach is more appropriate, especially in the boundaries between low- and high-Arctic due to the lack of dark night along polar days (where the light is / is not respectively a limiting factor for the plant growth). Since there are few methods with an unclear precision, an evaluation study on the effect of using different partitioning approaches along latitudinal gradients would be very beneficial to assess the suitability for each method.~~

4.3 Environmental forcing

Our data indicates that the importance of the main environmental controls (radiation and temperature) for C fluxes did vary across diurnal, seasonal and annual cycles, but also between time aggregations. The hourly variability of NEE and GPP (Figures 7 and 8) has been found to bewas mostly dependent on PAR because of the threshold nature on radiation control on GPP. Overall, the results indicate that environmental factors that can change rapidly such as PAR will have a high influence on short time scales (Stoy et al., 2014). In Figure 8, PARThe increased importance of PAR at 08 h and 20 h WGST, coincidinges with the sharp gradient in light at dawn and dusk (Figure 8). The control of PAR on GPP is not a new finding itself, but the Random Forest approach helps to quantify its importance. There is no GPP at night, and therefore there will be a strong increase/decrease in GPP at dawn/dusk. The seasonal pattern also showed that radiation is the single main driver for NEE and GPP between early June and early October, supported by the longer day-time. Further, PAR appeared to be a limiting factor for annual NEE in 2011, increasing morefurther even the complexity around this anomalous year. These results agree with literature (Groendahl et al., 2007; Stoy et al., 2014) suggesting that the uptake of CO_2 is partially controlled by radiation for the photosynthetic physiology at the leaf scale. Arctic plants are usually well adapted to environments with low light levels, reporting near-maximum rates ranging from 10°C to 25°C (Oechel and Billings, 1992; Shaver and Kummerow, 1992).

In terms of temperature, the pPhotosynthesis is restricted by low temperature, so enzymatically driven processes such as carbon fixation are more sensitive to low temperature than the light-driven biophysical reactions (Chapin et al., 2011). In this paper the daily, weekly, and monthly aggregated variability of C fluxes was primarily linked to T_{air}. Moreover, the Random Forest analyses revealed a strong diurnal pattern with a marked contribution of T_{air} to variations in NEE and GPP (both at night-time and between 08-18 h WGST). These results agree with Lindroth et al (2007), who recognized T_{air} as key driver for NEE seasonal trends in northern peatlands. However, in this analysis both NEE and GPP had similar responses to common environmental forcing, contrary to the results in Reichstein et al. (2007). In order to circumvent the potential circularity conflicts based on the use of partitioning products, we filtered day-time NEE (true GPP) and night-time NEE (true R_{eco}), obtaining very similar results (Table S2; supplementary material). Further, our data also suggest that R_{eco} is often dominated by air temperature. The patterns observed here are in agreement with findings on plant respiration dynamics (Heskel et al., 2016; Lloyd and Taylor, 1994; Tjoelker et al., 2001).

The analyses at different temporal scales demonstrate distinct C flux responses to different environmental forcing. The hourly variability of NEE and GPP has been found to be mostly dependent on PAR, while R_{eco} was linked to T_{air} primarily. In order to circumvent the potential circularity conflicts based on the use of partitioning products, we filtered day-time NEE (true GPP) and night-time NEE (true R_{eco}), obtaining very similar results (Table S2, supplementary material). On the other hand, the daily, weekly, and monthly C flux variability were mainly driven by T_{air}. These results entirely agree with Lindroth et al (2007), who recognized T_{air} as a main driver for NEE seasonal trends in northern peatlands. Overall, the results indicate that environmental factors that can change rapidly (e.g. PAR) will have a high influence on short time scales. Regarding temperatures, the photosynthesis is restricted by low temperatures, so enzymatically driven processes such as carbon fixation are more sensitive to low temperatures than the light-driven biophysical reactions (Chapin et al., 2011).

The changes of environmental forcing across diurnal, seasonal and annual time scales unmask patterns of functional responses to C fluxes. Interestingly the Random Forest analyses revealed a strong diurnal pattern with a marked contribution of T_{air} to variations in NEE and GPP (both at night-time and between 08-18 h WGST) while T_{air} was more important involving R_{eco}. It is also interesting to see how PAR increased importance at 08 h and 20 h WGST, coinciding with the sharp gradient in light at dawn and dusk. The seasonal pattern showed PAR as the single main driver for NEE and GPP between early June and early October, supported by the longer day-time and the decrease in cloudiness.

In this study, environmental drivers related to water availability such as VPD and precipitationsprecipitation were not found to be as influential as other assessed variables. We have not founddid not find significant relationships between CO_2 fluxes and the water table depth~~ either~~. Thus, there was no~~t~~ apparent water limitation on carbon dynamics during the eight years period. However, the complex interactions based on changes in temperature and soil moisture ~~regarding C dynamics seems to be still not fully understood~~particularly over full annual cycles and for sites with permafrost, ~~and these~~ should be further explored~~ in the Arctic tundra context~~. Our results contrast with Strachan et al. (2015) who described water table depth as an important driver regulating the CO_2 balance and others who found that CO_2 emissions increase during dry years due to increased decomposition rates and a reduction in GPP (Aurela et al., 2007; Lund et al., 2007; Oechel et al., 1993; Peichl et al., 2014); whereas other sites act as sinks during relatively wet years (Lafleur et al., 1997). The fen in Kobbefjord is probably quite resistant to droughts since it is fed with water from the surroundings.

5 Conclusions

~~An improvement in our understanding of the C balance in the Arctic, and its climate sensitivity, is important for understanding the response of tundra ecosystems to a changing climate.~~ We have analyzed eight snow-free periods in eight consecutive years in a West Greenland tundra (64° N) focusing on the net ecosystem exchange (NEE) of CO_2 and its photosynthetic inputs (GPP) and respiration outputs (R_{eco}). Here, the NEE gap-filling exposed inherent uncertainties in the seasonal C budget calculation, but there were also inconsistencies between the flux partitioning approaches used. We find that Kobbefjord acted as a consistent sink of CO_2,~~ accumulating –30 g C m^{-2} on average (range –17 to –41 g C m^{-2})~~ during the years 2008-2015, except 2011 that was associated with a major pest outbreak. The results do not show a marked meteorological effect on the net C uptake. However, ~~The~~ the relative insensitivity of NEE ~~was a compensation between~~during the snow-free period was driven by the correlated, balancing response~~s~~ of GPP and R_{eco}, both more variable than NEE and sensitive to temperature and insolation. ~~The ranges in annual GPP (–182 to –316 g C m^{-2}) and R_{eco} (144 to 279 g C m^{-2}) were >5 fold larger and more variable (CV are 3.6 and 4.1 % respectively) than for NEE (0.7%). GPP and R_{eco} were sensitive to the insolation and the temperatures and, interestingly, it was found~~In this paper we show a tendency towards larger GPP and R_{eco} during wetter and warmer years. The anomalous year~~,~~ 2011, affected by a biological disturbance, constituted a relatively strong source for CO_2 ~~(41 g C m^{-2}) and could partially~~and ~~has decreased its C sink strength due to the biological disturbance, which~~ reduced GPP more strongly than R_{eco}. A novel analysis assessing t~~The importance of variables at different temporal scales revealed differences in behavior depending on the time aggregation utilized. PAR dominated NEE and GPP while T_{air} correlated the most with R_{eco} in hourly averages, whereas T_{air} became increasingly important at coarser temporal aggregations for all the fluxes. T~~he changes of environmental forcing across diurnal, seasonal and annual time scales unmasked patterns of functional responses to C fluxes.

Despite the fact that we ~~have~~ analysed an eight-year dataset, the results ~~should be taken cautiously due to the incomplete pictur~~do not provide a complete picture~~e~~ ~~based on~~due to the lack of year round ~~year~~ data (Grøndahl et al., 2008). ~~Even when wintertime is not as critical as summertime period, this part of the year~~ The snow season should be taken into account for a comprehensive understanding of complete C ~~budgets~~budget (Aurela et al., 2002; Commane et al., 2017; Zona et al., 2016) and the delayed effect of wintertime-based variables such as snow depth or snow cover on the C fluxes. ~~Since~~ Because some studies have suggested that GPP and R_{eco} have increased with observed changes in climate and NEE trends remain unclear (Lund et al., 2012), it is challenging to ~~come up~~produce ~~with~~ strong ~~evidences~~evidence while the data remains scarce and fragmented. Hence, there is a need for increased efforts in monitoring of Arctic ecosystem changes over the full annual cycle (Euskirchen et al., 2012; Grøndahl et al., 2008). Future work ~~will~~ is also required with~~include~~ C flux modelling in order to ~~dig~~ explore into process-based insights of C exchange balance in the Arctic tundra, and the interactions of photosynthesis and R_{eco} with changes in C stocks.

Author contribution

E. López-Blanco, M. Lund, M. Williams, T.R. Christensen and M.~~T~~P. Tamstorf designed the experiment. Data preparation and analysis was primarily performed by E. López-Blanco with contribution from M. Lund (eddy covariance data processing, data quality control and LRC partitioning), M. Williams and T.R. Christensen (experimental set up), B.U. Hansen (data gathering from Nuuk Ecological Research Operations, GeoBasis), A.Westergaard-Nielsen (daily estimate of the timing of snowmelt) and J.-F. Exbrayat (Random Forest approach). E. López-Blanco prepared the manuscript with active contributions from all co-authors.

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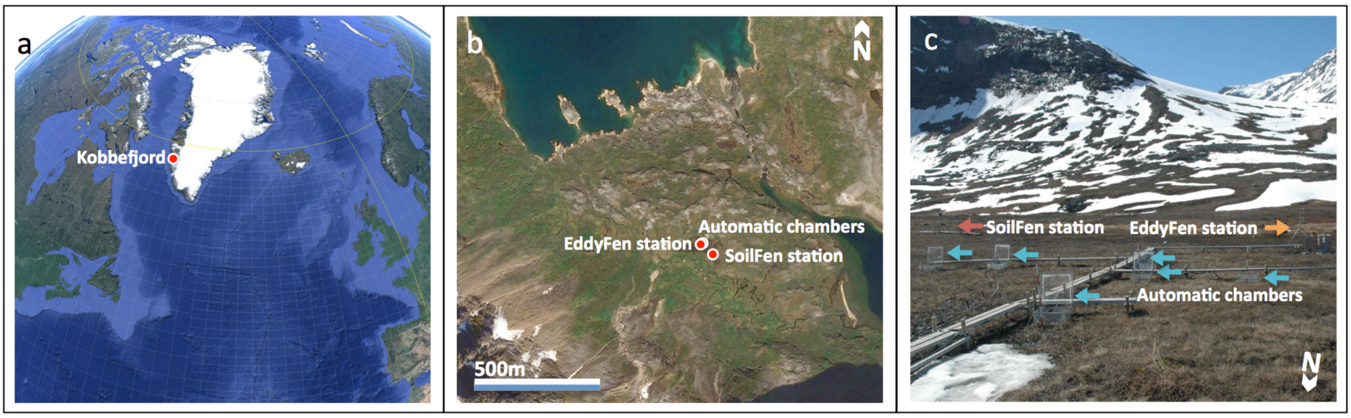
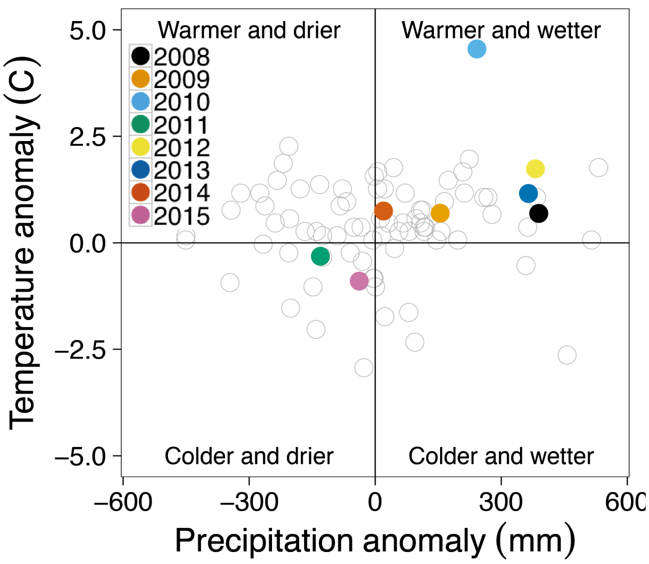


Figure 1: (a) Location of Kobbefjord in Greenland, 64° 07' N; 51° 21' W (Source: Google Earth Pro). (b) Location of EddyFen station, automatic chambers and SoilFen station in Kobbefjord (Source: Google Earth Pro, 16-07-2013). (c) Eddy covariance (orange arrow) from EddyFen station, six automatic chambers (light blue arrows) and SoilFen station (pale red arrow)(photo by Efrén López Blanco, 27-06-2015).



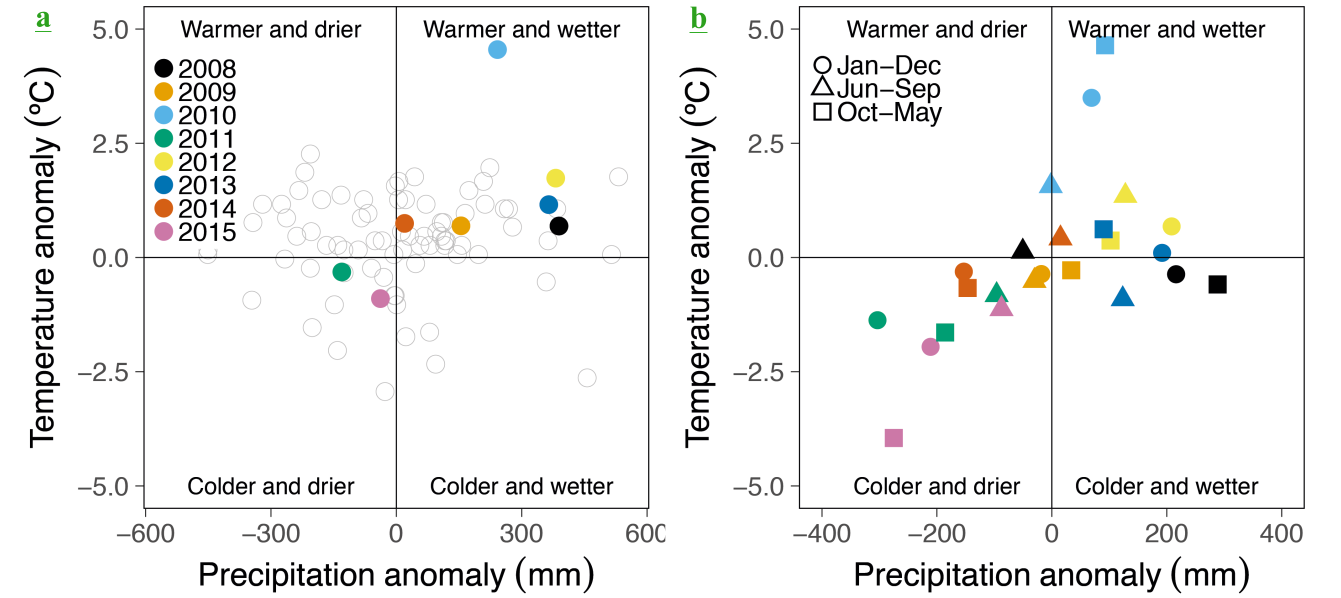


Figure 2: (a) Annual Temperature (°C) and precipitation (mm) anomalies of the analyzed years (2008-2015) compared to the 1866-2007 time series shown as empty circles (Cappelen, 2016~~).~~), and (b) within the 2008-2015 period including annual (January to December), warm season (July to September) and cold season (October to May) averages.

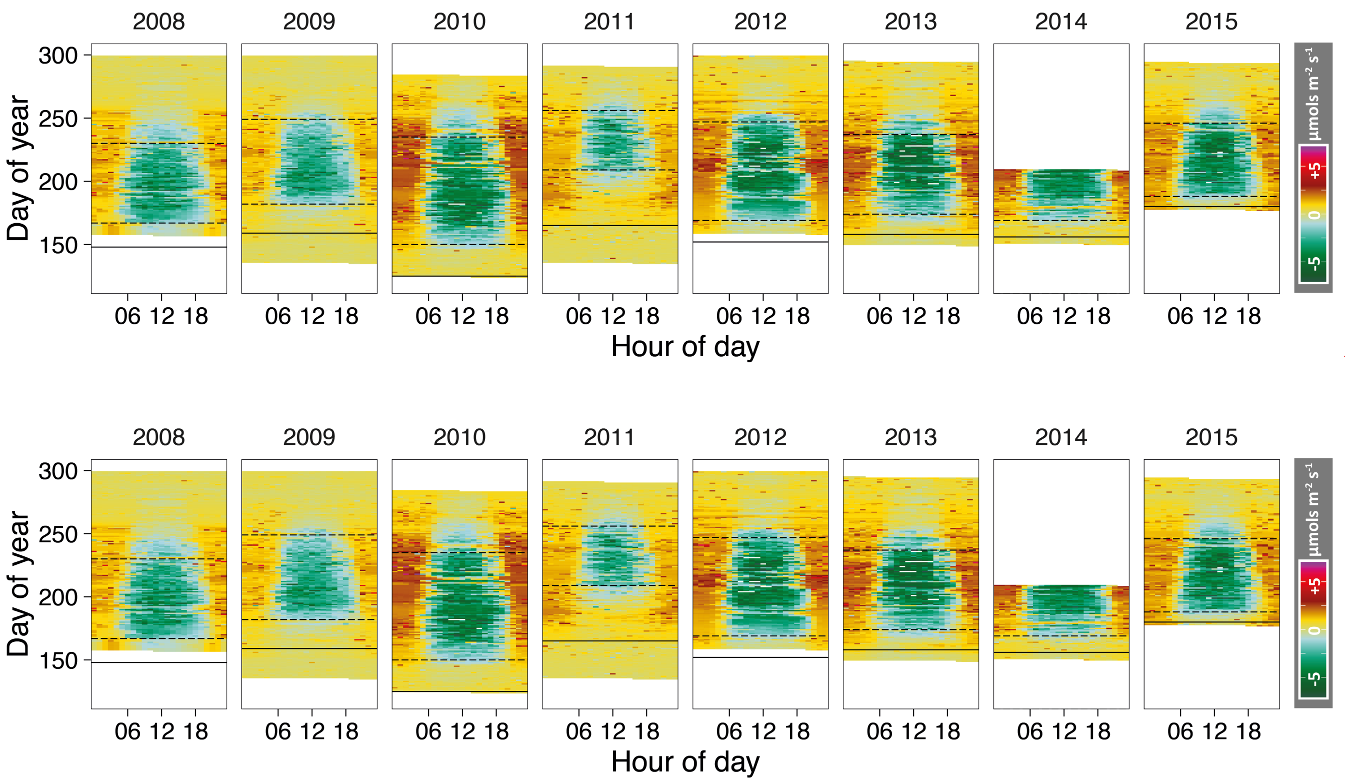
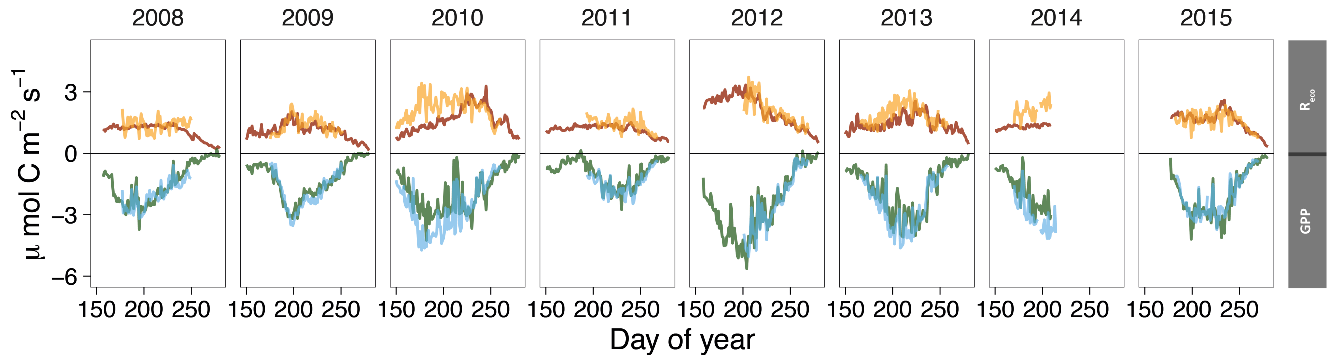


Figure 3. Time series of gap-filled NEE (2008-2015) based on auto-chamber data (2010-2013) and the MDS algorithm (from REddyProc). Green represents C uptake while the orange-dark red denotes C release. The solid lines represent the end of the ~~snow-melt~~snowmelt period while the area within the dashed lines represent the period between the start and the end of the growing season.



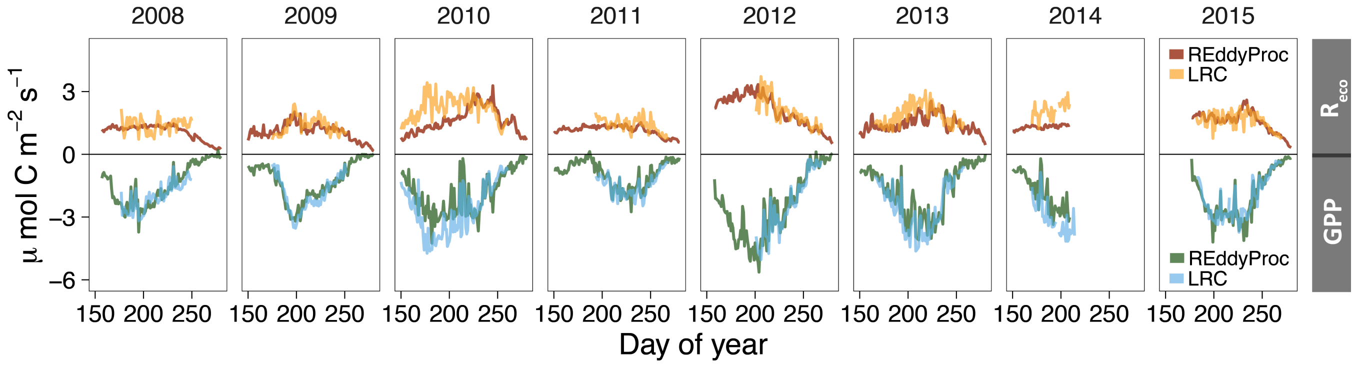
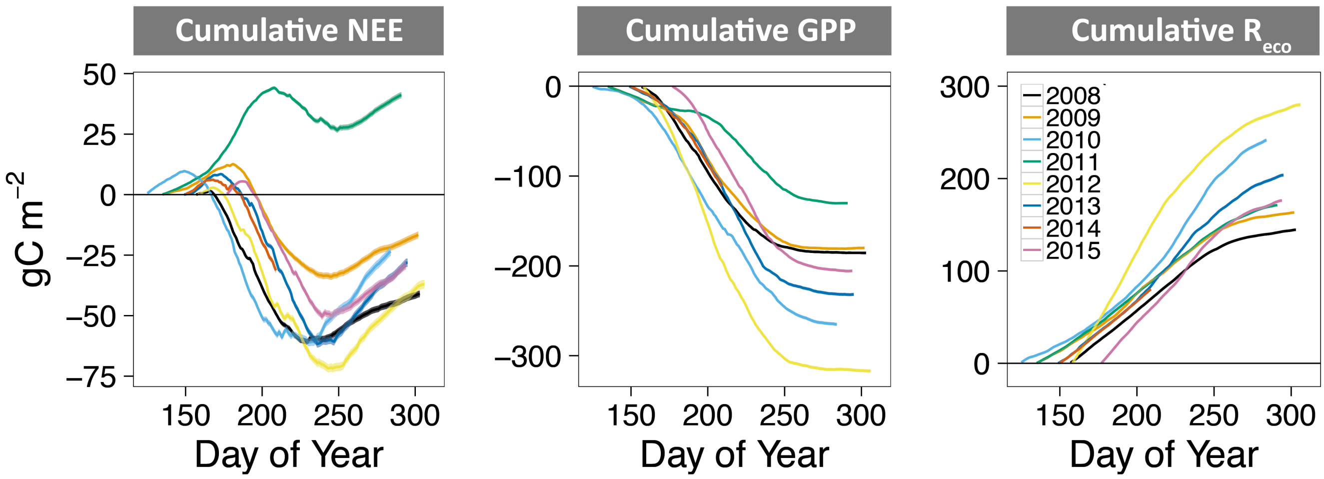


Figure 4. Time series of daily mean GPP (negative fluxes) and R_{eco} (positive fluxes) from 2008 to 2015 calculated by REddyProc (dark green and dark red) and LRC (orange and light blue).



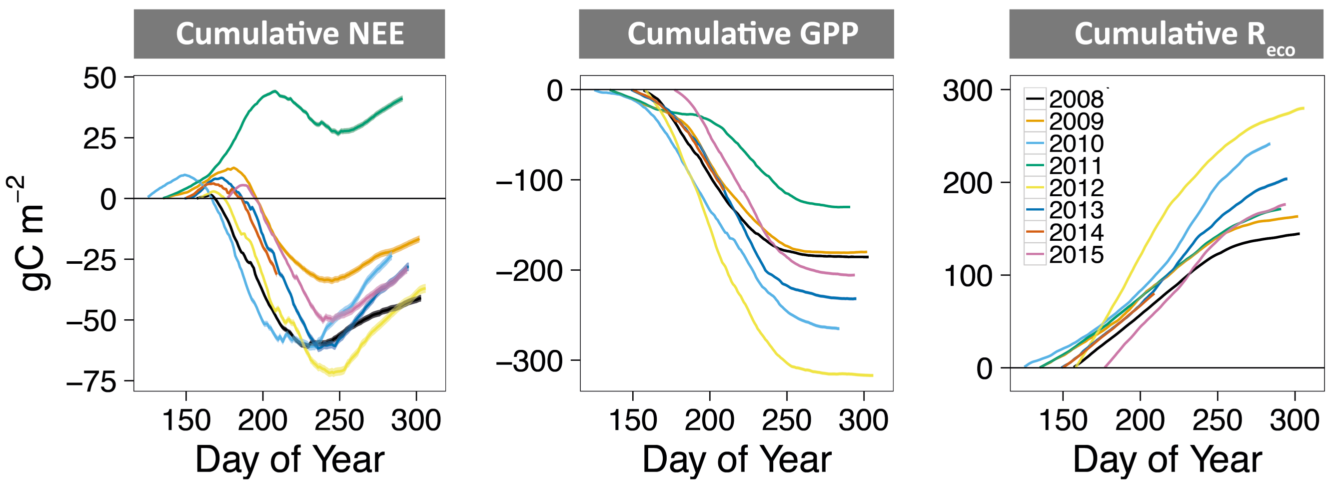


Figure 5. Cumulative NEE, GPP, and R_{eco} from 2008 through 2015 including the u* filtering and random errors.

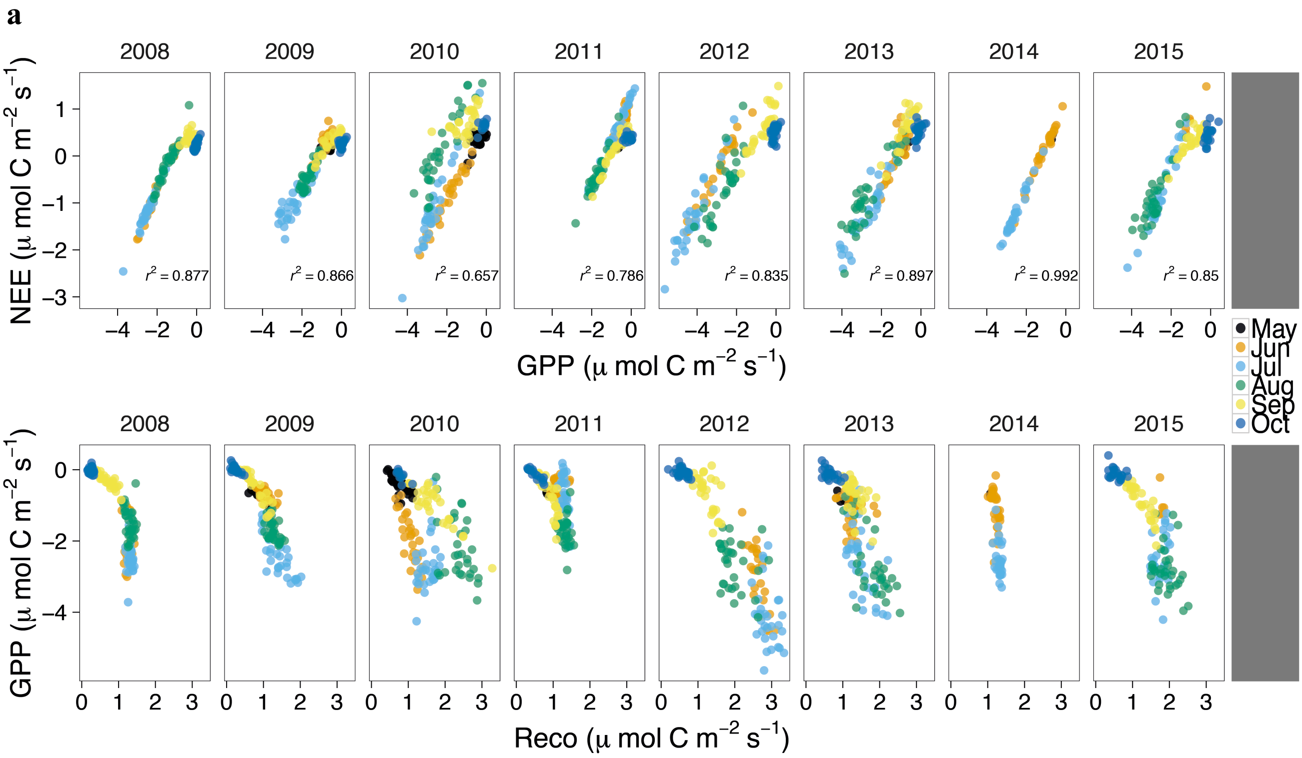
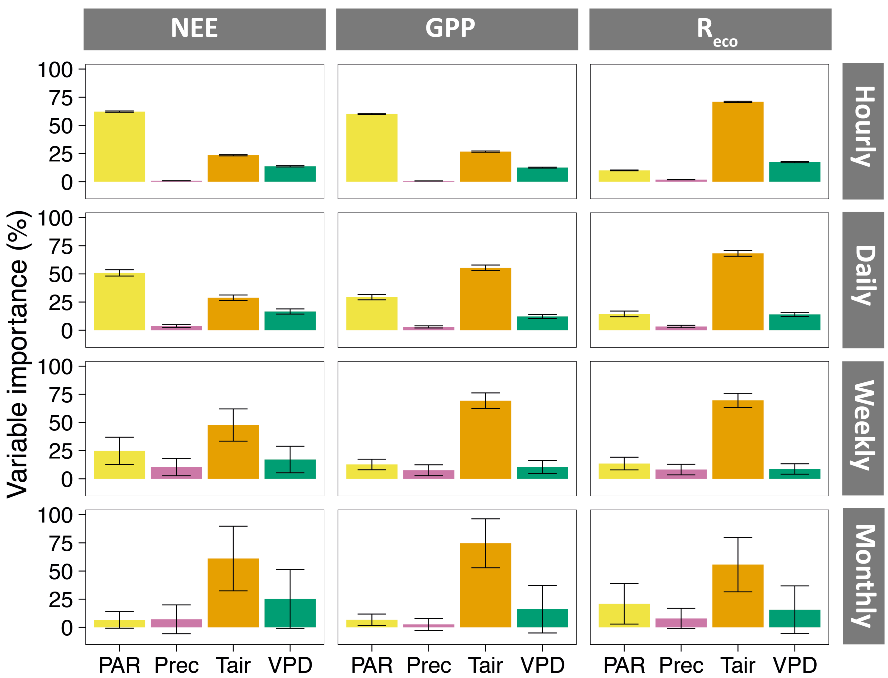


Figure 6. Inter-annual variability between (a) NEE-GPP and (b) GPP-R_{eco} relationships. The data was daily aggregated and colored per month



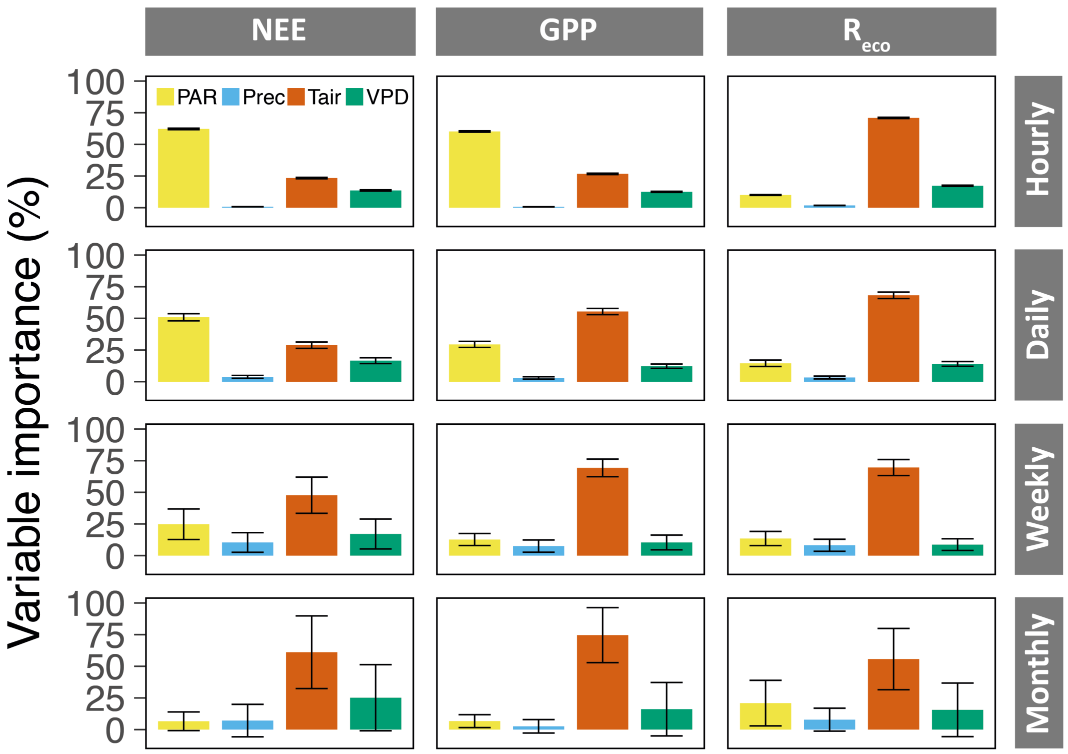
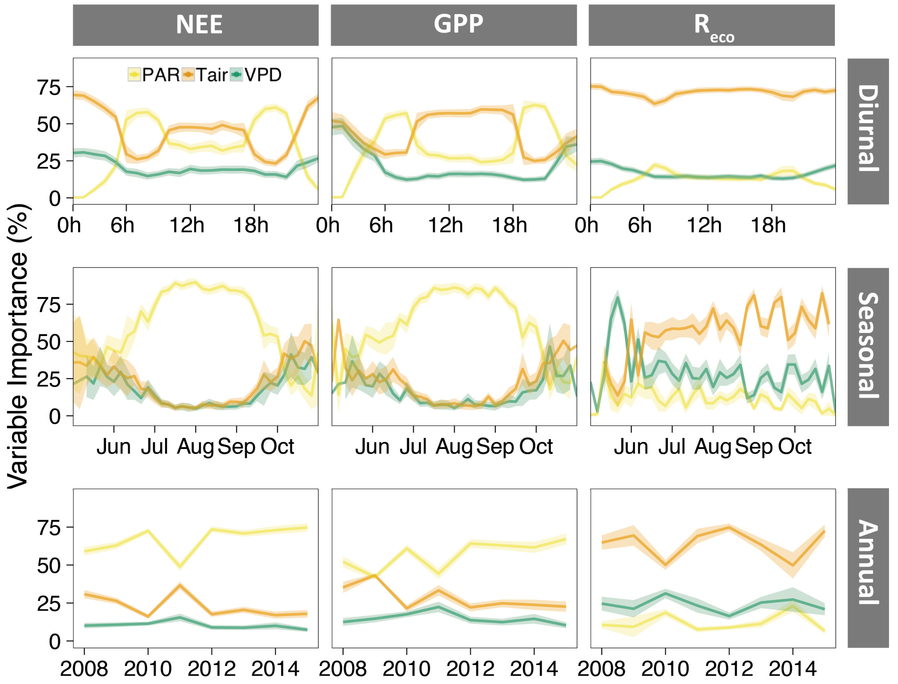


Figure 7. Importance of environmental variables PAR (yellow), T_{air} (~~Orange~~orange), Prec (pink) and VPD (green) to explain variability in NEE, GPP and R_{eco} (partitioned by REddyproc) at different temporal aggregations (hourly, daily, weekly and monthly) when all the years were lumped together. Thick bars and error bars represent the mean ± standard deviation of the importance across 1000 decision trees.



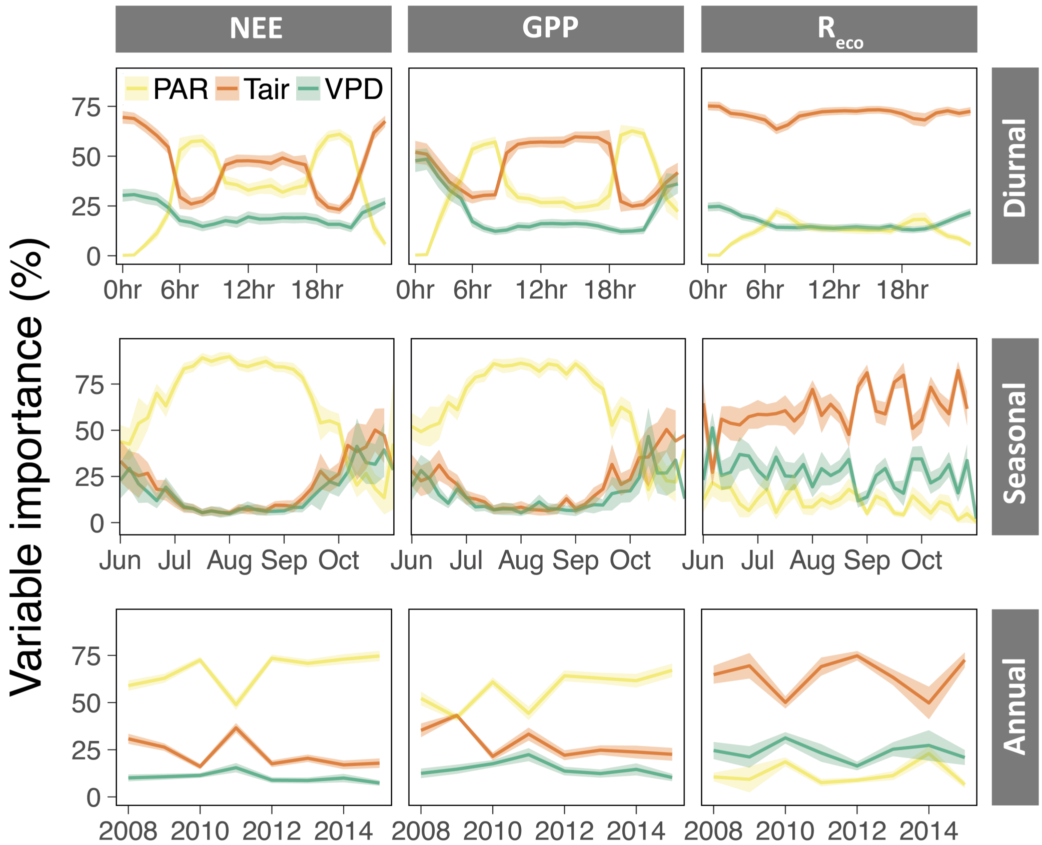


Figure 8. Diurnal, seasonal and annual importance of environmental variables PAR (yellow), T_{air} (~~Orange~~orange), and VPD (green) to explain variability in NEE, GPP and R_{eco}. Thick lines and shading represent the mean ± standard deviation of the importance across 1000 decision trees.

Table 1. Summary of the ~~phenological~~phenology-related variables for the period 2008-2015.

	2008	2009	2010	2011	2012	2013	2014	2015
Maximum snow depth (m)	0.6	1.0	0.3	1.4	1.0	0.6	1.1	1.2
~~Maximum snow depth (m)~~	~~0.6~~	~~1.0~~	~~0.3~~	~~1.4~~	~~1.0~~	~~0.6~~	~~1.1~~	~~1.2~~
End of snowmelt period (DOY)	148	159	125	165	152	158	156	176
Beginning of growing season (DOY)	167	182	150	209	169	174	169	188
End of growing season (DOY)	230	249	235	256	247	237	-	246
Length of growing season (DOY)	63	67	85	47	78	63	-	58

~~**Table 2. Summary of the measuring periods and the growing season CO2 fluxes for the period 2008-2015.**~~

Table 2. Summary of the measuring periods and the growing season CO2 fluxes for the period 2008-2015. ~~where applicable: ± sum of the auto-chamber, random and u* filtering uncertainties, *~~

	2008	2009	2010	2011	2012	2013	2014	2015
First measurement (DOY)	157	135	124	135	158	149	150	177
Last measurement (DOY)	303	304	282	287	305	295	209*	294
Missing data (%)	57.6	42.3	28.6	35.4	32.3	29.8	44.9*	40.0
NEE in measuring period (g C m^{-2})	-41.3	-16.9	-24.4	40.7	-37.0	-28.1	-28.7*	-31.5
	±1.4	±1.4	±1.9	±1.3	±1.8	±1.7	±1.1	±1.6
NEE in growing season (g C m^{-2})	-62.3	-45.9	-70.0	-16.2	-74.2	-69.7	-35.3*	-55.8
Maximum daily uptake (DOY)	195	205	182	230	204	220	192*	199
Maximum uptake (µmols m^{-2} s^{-1})	-2.4	-1.7	-3.0	-1.4	-2.8	-2.5	-1.9*	-2.3
Estimated GPP (g C m^{-2})	-185.5	-181.8	-266.1	-130.6	-316.2	-230.7	-106.8*	-206.1
	±1.4	±1.4	±1.9	±1.3	±1.9	±1.7	±1.1	±1.6
Estimated R_{eco} (g C m^{-2})	144.2	164.9	241.6	171.3	279.2	202.6	78.1*	174.6
	±1.3	±1.3	±1.8	±1.2	±1.8	±1.7	±1.1	±1.5

where applicable: ± sum of the auto-chamber, random and u* filtering uncertainties, * incomplete growing season dataset.

~~incomplete growing season dataset.~~