

General comments

The authors present an interesting perspective on ecosystem carbon exchange by analysing temporal asymmetry in net ecosystem production, and obtained interesting results. The paper is of good quality, well structured, concise, and the language use is clear. The introduction is to the point, and the methodology mostly provides a clear description of the followed procedures.

There are however quite a few smaller (but still important) matters that are unclear to me. Something that can still be improved in my opinion is providing additional information on some of the averaging procedures (how exactly the data is averaged). Furthermore, the distinction between explanations that can directly be derived from the data/results and hypotheses from the authors is not always clear in the discussion in my opinion. For some citations, it is not immediately clear to me how they support the corresponding statements. Below follow specific comments including details of the above, which will hopefully prove useful to further improve the manuscript.

Specific remarks:

Line 14: What do you mean with 'emergent property' here?

Line 18: The authors mention that every year about 14% of the carbon in the atmosphere is exchanged with the terrestrial biosphere. For this claim they refer to Lian et al. (2023). Could you please point me to the precise location in the Lian et al. manuscript where this info can be obtained from?

Line 19: Personally, I find the sequence here somewhat confusing and perhaps incorrect. At line 18, the exchange flux that is referred to is the gross exchange – the authors mention about 14% of the carbon in the atmosphere is exchanged with the terrestrial biosphere every year. And at line 19 the authors refer to this exchange as Net Ecosystem Productivity...

Line 27: 'the shape of the daily NEP trajectory ... ecophysiological controls that cannot be captured by aggregated totals alone (Dietze et al., 2011; Braswell et al., 2005; Wehr et al., 2016)' This statement is fine, but I do wonder whether the cited references are appropriate citations for this statement. If so, could you please give a brief explanation (or indicate specific sections of the cited manuscripts) showing these are appropriate citations. The same holds for the references on lines 30 and 31.

Line 34: I suggest to slightly rewrite the sentence 'GPP and RECO respond differently to environmental drivers with different sensitivities and on different timescales throughout the day...', to make it more clear. Currently it is not fully clear whether you mean 'sensitivities of the drivers' or sensitivities of GPP and RECO. Next to that, it is not fully clear to me to what 'Their' refers on line 36.

Line 35: Similar to one of my previous remarks, may I ask for some information on why you refer to Braswell et al. (2005) here? And to Rastetter et al. (2023) on line 64?

Line 77: 'Within the context of NEP variability these approaches provide effective measures' ... Do you use these approaches (theories for non-equilibrium fluctuations, fluctuation theorem) in this manuscript? When reading this paragraph I would expect so, but from the methodology section I tend to think you do not? Perhaps this can be made more clear? Please keep in mind that I am not familiar with the fluctuation theorem etc., which might also (partly) explain why this looks somewhat contradictory to me.

Line 86: Could you perhaps explain what you mean with ‘with no reference to either deterministic or stochastic components’? In case you think the explanation is relevant to the reader, you can perhaps include the explanation in the text.

Line 87: This is not fully clear to me. When referring to 99th quantile of NEP, to what extent are the values aggregated, i.e. hourly NEP values, minutely values,...? Reading on in the manuscript I found out that the data are half hourly. Do you pool all the half hourly NEP values over the years, and calculate the 99th quantile from this data set? If this is indeed what you did, doesn’t this mean that a lot of the summer midday values (even those of relatively normal summer days) end up in the 1% most extreme NEP values? Perhaps this can be made somewhat more clear

Line 87: What do you mean with ‘without reference to climatic extremes’?

Line 96: ‘that met a set of criteria as of June 6th, 2024’ ... Do these sites meet the criteria throughout the whole period for which data was used?

Line 105 vs 115: Perhaps check whether there is information that is unnecessarily repeated

Line 110: You indicate that you downloaded respiration and GPP data. Where in your analysis do you use the GPP and RECO data? Or do you only use the NEE data?

Line 111 and 102: Is it true that for variables other than SWC and soil temperature, you did not restrict the selection to records with quality flag ≤ 1 ? If not true, these sentences are written somewhat incorrect or ambiguous in my opinion. For example, line 102 can be read as ‘soil temperature and soil water content (...) data that were gap-filled only with high confidence...’. Thus, the ‘that were gap-filled’ referring to soil temperature and SWC. But the sentence was perhaps rather meant to indicate that the full dataset is restricted to carbon flux records that were gap-filled only with high confidence. A similar issue applies to Line 111. If it are only SWC and soil temperature that are restricted to quality flag ≤ 1 , is there a specific reason why you did this only for those variables? It would be good to make sure that the sentences from Line 102 and 111 are clear.

The heading of Section 2.1 (Data and site selection) might not fully cover the content, i.e. the method of quantifying asymmetry is also discussed here. This can perhaps be made more clear in the heading.

Line 127: Does irreversibility here refer to the fact that the fluctuation path cannot be followed in reverse order? I assume it does not refer to the state of the system being permanently altered, as NEP can in principle return to pre-fluctuation values?

Line 128: ‘applies’ or ‘is applied’? Does the approach really not apply to the partitioned components, or is it just better to apply it to NEE directly because of the potential biases in GPP and RECO?

Line 130: I very much like the extensive explanation that is given about the fluctuations, and the illustration of the asymmetry calculation procedure in Figure 1.

Line 137: What do you do when two NEP peaks are present (crossing the threshold) temporally close to each other (e.g. half an hour apart) within the same 12h time period? Do you then calculate 2 fluctuation paths and count both paths as two fluctuations (although largely overlapping) for your statistics? Or do you simply take the highest peak within the 12h time period to calculate a single fluctuation path?

Caption Figure 1: Is the description given for (b) fully accurate? The authors mention ‘Sample half-hourly NEP time-series over one day, showing a large fluctuation (red) that exceeds the NEP

threshold and a smaller fluctuation (black) that does not.’ The total fluctuation path is shown in red here and the rest in black, isn’t it?

Caption Figure 1: ‘Folded fluctuation path showing the rising and falling limbs overlaid about the peak’ ... Perhaps this is not fully accurate. I see the rising limb (blue full line), the falling limb (orange line) and the rising limb mirrored around the peak (blue dashed line). Maybe good to make this clear.

Caption Figure 1: The step that is not fully clear in the Figure is the normalisation of NEP values applied in Eq. 2. Perhaps you can make it clear in the caption that in subfigures (c) to (e) the NEP values are normalised with peak NEP.

Figure 1e: whitespace missing in the y-axis title and check upright vs cursive part of axis title

Line 146: Maybe the flow of the text would be more clear if you would first show Eq. 3 and introduce how you calculate the asymmetry, before you mention the averaging. But this is merely a suggestion, if you think it is more clear the way it is written now then I’m of course fine with it.

Line 148: I understand that random errors in the timing of the peak will cancel out when averaging. But what if you have a single data point that peaks above the threshold due to a measurement error (e.g. in the evening)? I assume that will then be an erroneous fluctuation that will be included in the statistics? Also at this point in the manuscript I do not understand over what you average? Over all identified fluctuations in the three year periods? Perhaps this can be made somewhat more clear

Line 155: ‘for each fluctuation path (or directly for the average fluctuation path) we folded...’ When do you calculate it using the average fluctuation path directly and when do you calculate it for each fluctuation path? For the results in Figure 3, did you use the average directly? Can the reader derive this from the context?

Line 165: Given that you indicate here that you analyzed max of A_t for **each** fluctuation path, should the overbar be removed here? Or should the overbar be kept and the text slightly changed instead? A similar issue occurs for step 4.1 in Table S4, there is no reference to averaging.

Line 176: Why necessarily moderate flux magnitudes?

Line 178: ‘attenuate rather than amplify the patterns’ ... I understand it will dampen the extreme NEP values, but whether it would attenuate patterns in asymmetry is another step that I do not immediately see.

Line 180: What mean did you use? The mean over all data available for each site?

Line 189: Personally, I would like to see a bit more information about the averaging, i.e. you mention you average over three years. But, this can mean multiple things, i.e. you can calculate a single value for the three-year period, or you can create an averaged day with half-hourly values, or you can create an averaged day for each month. I would like to have a bit more details, because at this point in the manuscript it is not clear to me (it becomes more clear when seeing the Figures).

Line 190: Why the word potential here?

Line 191: What do you mean with ‘maximum photosynthetic thresholds’ and how does the Duffy et al. (2021) reference support this statement?

Line 195: You refer to Tables S6 and S7 here, but these tables do not show a comparison between matching averages and full-record averages?

Line 202: Not sure if I'm interpreting this correctly, but in case two models have an equal BIC value, you start looking at AIC, adjusted R², and RMSE? Is there also priority in the latter three criteria, e.g. looking at AIC first (after BIC)? This is not really clear to me from the text.

Figure 2: Regarding the right (pdf) part of the figure, I assume it shares the y-axis of the left part of the figure (would be logical). However, in the pdf I see non-zero (around 10⁻³) pdf values for grassland for NEP values as low as -20, while in the left part of the plot I don't see any fluctuations for grassland that go anywhere near as low as -20. What is the explanation for this?

Figure 2 (caption): 'Sample time-series of NEP for four selected sites' ... I see here data for 4 biomes. Are these 'biomes' a combination of multiple sites having the same biome? In Figure 3 I see that 13 sites and 7 biomes are plotted. I think it would be good to make clear somewhere that these biomes present a combination of some of the used sites (at least, if it is true what I'm assuming).

Line 206: sites or biomes?

Line 219: 'c = 99% quantile' ... I assume you mean that c is chosen such that only values in the 99% quantile are selected? Same for line 307 and caption Figure 6. But ok, it is quite clear what is meant.

Line 220: Here and throughout the manuscript it seems to be assumed that the peak occurs around midday, with a morning rise and afternoon decline. This is not shown in Figure 3, as relative times are shown. Could you somehow show that a morning rise and afternoon decline is actually what the data shows (and maybe include this in the manuscript)? Does NEP already decline at the end of the morning?

Line 221: Why at least equally productive instead of more productive? Because you account for the possibility that respiration is higher in the morning? But then the afternoon could theoretically even be less productive.

Line 223: 'The same analysis shown separately for all 13 sites is presented as Figure S2 in the Supplementary Information' ... In Figure S2 the individual fluctuation paths are shown, perhaps an idea to make this clear when referring to the Figure. A similar suggestion applies to line 256.

Line 226: 'biome-specific differences under average conditions' ... Are they biome specific, i.e. do sites with the same biomes but different locations show large similarity under average conditions?

Line 231: Based on the figure, the max asymmetry looks more like 0.4 than 0.5 (for the site with highest max asymmetry).

Line 237: 'This elevated asymmetry may arise from enhanced afternoon respiration during warm winter days' ... I struggle with this theory. We are talking about the top 1% NEP fluctuations, i.e. moments when there is a large carbon sink (positive NEP). Now if in the afternoon respiration is enhanced as you suggest, then the sink strength would decrease, right? This would lead to negative asymmetry (or less positive) rather than stronger positive asymmetry, right? If you agree, then please adapt or remove this theory.

Line 238: 'Similar asymmetry is observed when analyzing the top 2% and 5 %, although with a lower magnitude (Figure S6 in Supplementary Information),' Perhaps you should add the word 'generally' here, as in Figure S6a and S6L the asymmetry magnitude for the top 5% is most of the time higher than for the top 1%. Next to that, I suggest to indicate in Figure S6 or in its caption which plot corresponds to which site. Also, I suggest to indicate in the description above the figure that the all fluctuations line (c=0) is also plotted.

Line 243: I understand the importance of declining radiation, but 'declining radiation' is listed here as an example of the respiratory and regulatory processes. Could you shortly explain this?

Line 247: 'For example, lower temperatures limit both photosynthesis and respiration, resulting in relatively balanced rise and fall patterns and lower positive asymmetry' ... The step from 'lower temperatures limit both photosynthesis and respiration' to 'lower positive asymmetry' is too big in my opinion. I would argue that it also depends on how temperature behaves before and after the peak. Of course, when (absolute value of) NEP is low, the before vs afternoon differences in NEP will be small as well. However, with your Eq. 2 you normalise with NEP^{max} , so this does not mean that the asymmetry coefficient cannot be large. Can you explain in more detail in the text why you think lower temperatures lead to lower asymmetry?

Line 250: Similar to the above, perhaps explain in the text why a GPP-dominated situation leads to positive asymmetry.

Line 245: Given that you have all the temperature data etc, have you tried making a plot of temperature on the y-axis and time before and after the peak on the x-axis (separately for the 1% and for all fluctuations)? Do you see a similar asymmetry as in NEP?

Line 247: Could you provide some information on how the Koyama and Takemoto (2014) reference supports the statements here / why you refer to it?

Line 258: 'while respiration remains more steady' ... Or is it more likely that it even increases (higher temp in afternoon)? Is this something you deduced from the Fluxnet respiration data? Might be good to make this clear.

Line 262: 'The Savanna ecosystem (AU-DaS) has the highest negative asymmetry coefficient' ... I suggest to add the word 'generally' or 'for most of the time' here, as this does not hold at all times based on Fig 3d.

Figure S17: I don't understand why there is a difference between Figure S12b and Figure S17a. Aren't these supposed to be the same variables? And why are the asymmetries positive in Figure S17a? And why a Hill function in S17a and a linear function in S12b?

Figure S17: Daily VPD average is not plotted?

Figure 3: The legend indicates that 'CN-Qia' and 'Evergreen needle Forest' are plotted as full lines, but for one of them this is not true (see the actual lines in the figure).

Figure 3: I see that you put NEE_FP instead of NEP_FP on the y-axis? I assume it does not matter for the signs as they will cancel out due to the normalisation.

Figure 3: Please check the legend: According to the legend there should be 14 full lines in the figure panels. However, I only count 7, so apparently the legend symbols are not an accurate view of the actual lines. This makes it more difficult to identify the correct lines.

Line 273: Is there a reason why you include the overbar on A^{max} in Figure 4 but not in the text here?

Line 274: I suggest to refer to Table S6 here.

Line 276: At 22°, the curve seems closer to 0.35 than to 0.45... A typo? Or do you look at the data points instead of the curve (text mentions curve)?

Line 279: Similar to one of my previous remarks, I'm not sure whether I find the explanation sufficient here. I suggest that you provide a clear and elaborate explanation on why higher GPP produces higher asymmetry. Not necessarily at this point in the manuscript, it could also be earlier. Of course, larger GPP allows for larger differences in GPP before and after the peak. But given that the NEP values are normalised with NEP^{max} , this is on itself not a reason I assume. I also suggest you elaborate on 'the differential response between GPP and RECO saturates'.

Caption Figure 4: 'Statistical metrics for each fit are reported in the legend boxes' ... They seem to be missing?

Line 284: 'reflecting its role in steep morning NEP rises' ... yes, but to directly contribute to asymmetry, the afternoon descent should be less steep, right? And radiation is rather symmetric I assume.

Line 285 and 286: I don't really understand how VPD could reinforce positive asymmetry and show a positive correlation with A^{max} . My reasoning would be that under high VPD, photosynthesis would be depressed. High VPD values mostly occur in the afternoon (after the peak), when temperatures are high. Thus, under high VPD conditions I would expect a strong afternoon NEP decline, and thus a less positive or even negative asymmetry... Am I making a mistake in my reasoning?

Line 286: 'when coupled with high radiation' ... Is this based on reasoning, or is this based on some model test or so?

Line 293: You could also refer to Table S7

Line 303: the text mentions $r=-0.2$ for the T:P ratio. Figure S16 shows $r=-0.2624$ and $r=-0.3825$ for 3yr and daily data, respectively. Table S7 mentions $r=-0.2624$ and $r=-0.2111$ for 3yr and daily data, respectively. This is not fully consistent.

Line 310: Can't Reco be a part of the explanation as well? Have you analysed GPP and Reco separately? If not, it might be better to make clear that the text here is an hypothesis and does not directly follow from the data.

Line 311: 'These differing responses between extremes and typical daily peaks are due to differences in the timing of how photosynthesis and respiration respond to daily changes in the environmental drivers' ... Aren't it at the end the differences in the drivers between the extreme and daily situations that, via the GPP and RECO responses, lead to the observed difference in asymmetry between daily and extreme fluctuations?

Figure 5: Is there a reason why, for US-SRM, there are horizontal black bars below and above the box for top 1% fluctuations but not for the box of all fluctuations?

Figure 5: I don't understand why there is an overbar on A^{max} here. You show the distribution for each site with boxes, so where does the averaging happen?

Line 316: To what extent is this an hypothesis, or actual results? Do the data show an accelerated morning GPP rise when temperature is high, or is this an assumption? And similar, do the actual data show a steep afternoon GPP decline while RECO remains more steady in the 'average' (all fluctuations) situation?

Line 322: 'the amplitude of NEP fluctuations' ... there is a sign shift, so is the amplitude the most appropriate word here?

Line 329: 'sustains GPP under near-optimal conditions'?

Line 324: ‘...one in which NEP is governed primarily by changes in GPP (linked to temperature) and another in which RECO plays a larger role’ ... This sounds very plausible, but personally I don’t see data-based evidence whether this is really what is happening. Would it be possible to do an analysis (or give an explanation) that more explicitly proves that temperature-induced GPP changes are indeed the main reason for the positive asymmetry and Reco plays a larger role in the other case? If not, I suggest that you try to make it somewhat more clear that this a theory, and does not directly follow from the data. Or perhaps your statements follow from reasoning, but then I suggest you give a more full explanation.

Line 333: Regarding my point above, in this paragraph there is an additional argument supporting your statement that NEP is governed primarily by changes in GPP for the top 1% fluctuations, i.e. the logical but important reasoning that GPP should strongly exceed Reco in order to end up in the top 1% fluctuations. You could consider slightly changing the order of some of the information to make this clear earlier in the section.

Line 333-339: ‘Under such conditions, afternoon stomatal limitation is reduced because VPD is less likely to reach levels that trigger strong stomatal closure’ ... I understand that at the time of the peak, conditions should be very favourable for a high photosynthetic rate. However, this does not necessarily mean that a few hours later – after the peak – this is still the case, as e.g. VPD can be strongly increased. Are there convincing arguments for assuming favourable photosynthetic conditions over the whole fluctuation period instead of only around the peak?

Line 343: What is meant with cancellation artifacts here? And with ‘cancellation effects’ on line 346?

Line 350: Soil moisture is expressed here in mm instead of the more traditional m^3/m^3 or %. Can you explain these units, perhaps also in the manuscript? Or is it a typo?

Line 351: Does a low MAT:MAP ratio contributes to water limitation? Isn’t it the other way round?

Line 356: Is there a reason why you sometimes mention ‘MAT:MAP ratio’ and sometimes ‘T:P ratio’? Is the latter not averaged?

Line 356: Is the ‘very high shortwave radiation’ at US-SRC beneficial for sustained afternoon assimilation?

Supplementary Figure S16: Why is Au-Das only shown in panel (a)? And I assume the difference between panels (a) and (b) is that in (b) you calculate for every day the ratio and average afterwards over the days, while in (a) you calculate the mean T and mean P, after which you calculate the ratio? I suggest to explain this more.

Line 357: ‘US-SRC again deviates from expectation’ ... this seems to depend a lot on whether you take the daily ratio or 3yr ratio, for the daily ratios the point is relatively close to the line.

Line 358: ‘despite a relatively high T:P ratio (~ 600)’ ... Are you sure you did not mistakenly look at the AU-Rig datapoint instead of the US-SRC datapoint? Because, if I read the legend well, Us-SRC has a (3yr) MAT:MAP ratio above 1000.

Line 359: ‘reflecting the overriding influence of extremely high radiation’ ... Why would extremely high radiation lead to very negative asymmetry? Afternoon radiation will generally not be higher than morning radiation, so why would radiation depress GPP or increase Reco in the afternoon? Is the effect indirect via increasing VPD? Perhaps good to make this clear

Line 363: ‘...gap filled hourly values of NEE using’ ... You mentioned earlier that you use half-hourly NEE data. How do you go from the hourly to the half-hourly data?

Line 366: What do you mean with ‘over a few extreme fluxes’? These lines are not really clear to me.

Line 366: ‘If any of these values exceed the top 1%’ ... I assume ‘these values’ refers to the values of the missing data. And I assume that with ‘they would most likely reduce’ you mean the gap-filled values are most likely reduced compared to the original (unknown) fluxes. If you agree that these lines are currently not fully clear, perhaps they can be written slightly differently... But I probably don’t fully understand what you want to say here, especially the part about the bias.

Line 367: I understand the extreme values might be ‘dampened’ because of the averaging, but why a positive bias? When NEP is underestimated, isn’t it a negative bias? Or am I misunderstanding the reasoning here?

Line 366: If extreme meteorological conditions would be causing the extreme fluxes, than averaging over similarly extreme conditions would not decrease the fluxes? Are generally mostly less extreme conditions selected for calculating the average in such a case?

Line 371: But do you use also the RECO and GPP data (as they are not shown)?

Figure 6: I suggest to put arrow heads under the lines pointing to the word ‘temperature’, as you do for VPD

Figure 6 caption: ‘to temperature under extremes’ ... you could consider to write ‘to temperature under positive extremes’ or something similar, as you did not look to negative extremes

Figure 6 and e.g. line 374 in the text: I doubt somewhat whether we can firmly talk about a temperature driven regime in extreme conditions and a VPD-driven regime under normal conditions. Figure 4b indeed shows a pattern for VPD, but the curve fit is not super, and $r=-0.59$ is not overwhelmingly convincing either I would think. I know VPD gave the best fit of all variables for the typical conditions, but, based on the findings in this manuscript, can we really firmly talk about a VPD-driven regime and a temperature controlled regime? What is your view on this?

Line 392: Are you talking here about formulating a nonlinear response function of NEP to environmental drivers, e.g. temperature? How would you translate from asymmetry to actual NEP? I am not familiar with these types of analyses

Line 398: ‘Terrestrial biosphere models and machine learning techniques are common approaches to predict NEP’ ... you could consider giving an example reference

Line 403: ‘the tails of the NEP distribution that matter most under disturbance or climate extremes’ ... depends somewhat on the kind of climate extremes whether you end up in the NEP tails I would think.

Line 407: ‘typically associated to stronger environmental forcings’ ... or just more ideal conditions for sustaining high afternoon photosynthesis... is a stronger forcing typically required for that?

Line 412: What do you mean with strategies for sustaining carbon balance in this context? Is this desirable (e.g. net uptake might be better)? Perhaps check whether this sentence really states what you want it to.

Line 413: ‘Finally, while here we focused on ecosystems in their stationary state’ ... Are they indeed all in stationary state? Are do you rather mean relatively undisturbed?

Supplementary Table S3: In the definition of $A^{\max}$ (with overbar), there is no reference to ‘average’ given, while this is what the overbar indicates I assume.

Figure S12: I suggest to also refer to daily temperature average in the caption (you also refer to daily average variables in the captions of the other figures), instead of just to the 3-yr average

Technical remarks:

Line 71: ‘which have been proving useful’ ... ‘which have been proven useful’ instead?

Line 148: ‘The asymmetry metric’ instead of ‘The asymmetric metric’?

Line 215: ‘focus’ instead of ‘focuses’? Or alternatively, ‘analysis’ instead of ‘analyses’?

Line 223: full stop instead of comma after ‘biomes’?

Line 231: ‘reaching’ instead of ‘reaches’?

Line 349: ‘falls’ instead of ‘falling’ to make the sentence correct?

Line 369: ‘artifacts’ instead of ‘artifact’?

Line 387: Bracket should be moved in front of ‘Niu’. A similar issue on line 389.

Line 390: systems’ instead of system’s (and perhaps responses)? Depends on what you want to say, but the current sentence seems grammatically incorrect to me.

Figure 2: It seems there is a whitespace between C and O in the y-axis title that should not be there. Also, the ‘C’ seems to be upright text while the ‘O’ is cursive.

Caption Figure 6: Please check the font of Q_{NEP} .

Supplementary Table S1: ‘MEAN NEP FOR STUDIED PERIOD ($\mu\text{molCO}_2\text{m}^{-2}\text{s}^{-1}$)’ ... Please check subscript vs normal font.

In supplementary Table S3, it seems the overbar is missing for ‘The average asymmetry coefficient across all fluctuation paths’. At least, I don’t see it in the pdf on my computer.

Whitespace missing in heading Table S5: ‘top1%’, while the whitespace is included in the section title on the same page.

Table S4: Please check the placement of the formulas in the Table, part of the formula symbols are obscured

Table S4: Please check the formatting and missing overbar in the formula of step 3.2