Response to interactive comment by Anonymous Referee #2 on "Water stress induced breakdown of carbon-water relations: indicators from diurnal FLUXNET patterns"

This study proposes two data-driven indicators using eddy covariance data to examine water stress induced breakdown of carbon-water relations. These results are scientifically interesting. Sharing code is a also good practice and should be praised, although the calculations seem to be straightforward. Given the problems with the manuscript, I recommend that it be reconsidered after a major revision.

1. The biggest problem of this manuscript is that the Results section is very weak. It only contains three relatively short paragraphs, which is far from being sufficient for a research article. The authors should substantially strengthen this section.

As all of the reviewers have made this point, we have expanded this section considerably. First we have included a new section focused on a case study of the European heatwave of 2003, in which one can see morning shifts and decoupling of water and carbon at 6 sites across Europe (now Figure 3 in the new manuscript, here Figure (R1)). The following text has been added to the results in relation to this figure:

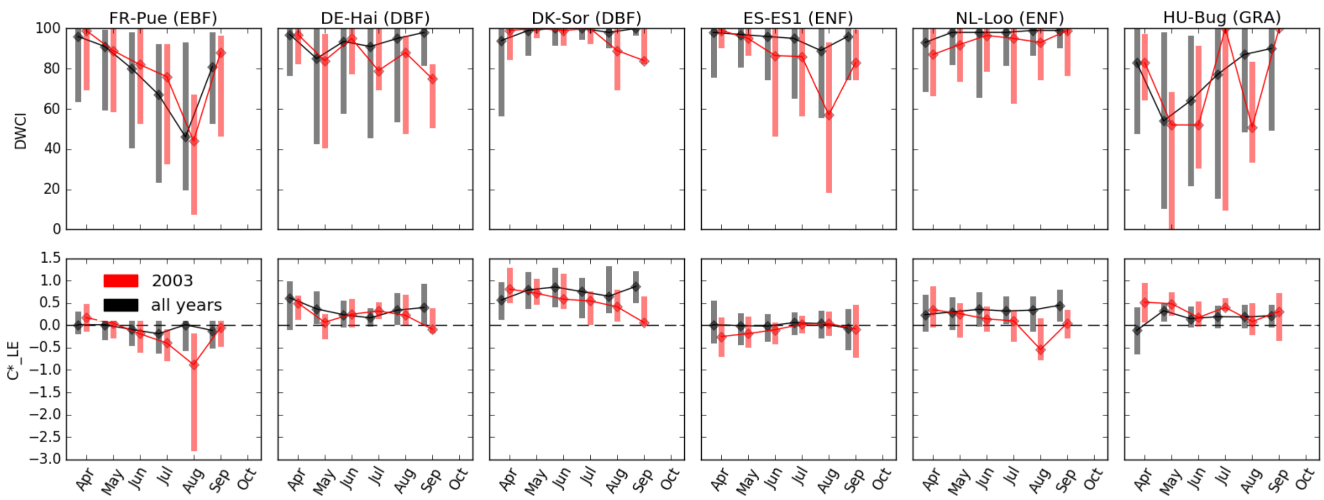

Figure R 1: Monthly median diurnal water carbon index (DWCI, lower panels) and diurnal centroids (C^*_{ET}, upper panels) for 6 sites in Europe. Data from all years available (black) is compared to 2003 (red) during which a drought event resulted in high temperatures and low precipitation throughout the summer. Note DWCI of 0-100 indicate lowest-highest probability of diurnal carbon:water coupling and C^*_{ET} of -1-1 indicate one hour morning shifted-one hour afternoon shifted ET. Vertical bars represent interquartile range. Sites from 5 plant functional types: evergreen broadleaf (EBF), deciduous broadleaf (DBF) and evergeen needleleaf (ENF) forests, as well as grasslands (GRA). Ecosystems show tendancies of morning shifts (e.g. DK-Sor and IT-Mal) and carbon:water decoupling (e.g. ES-ES1 and HU-Bug) during the drought year.

As a case study, C^*_{ET} and DWCI time-courses for eight sites from Europe are shown in Figure 3, with an emphasis on 2003 when the continent was struck by a heatwave that was shown to effect both the carbon and water cycles [1, 4, 2]. For DWCI, forest sties showed high water:carbon coupling throughout the growing season, with the exception of Peuchebon (FR-Pue) which showed a regular seasonal cycle of decoupling. The grassland site (HU-Bg) showed a higher variability in DWCI compared to the forest sites (all others). All sites showed either a decrease in median DWCI or an increase in variability during 2003, generally in July or August, particularly at Hainich (DE-Hai), Bugacpuszta (HU-Bug), and El Saler (ES-ES1). This increase in decoupling during 2003 is consistent with the hypothesis of non-stomatal limitations being expressed in hot, dry conditions. Median diurnal centroid values across all years varied in absolute magnitude, but were generally near or above zero, i.e. the water cycle showed no shift or an afternoon shift. One exception would be the Mediterranean oak forest of Puechabon, which shows a slight seasonal cycle of morning shifts going from a slight afternoon shift to a slight morning shift during June, July, and August. During drought years, sites that showed distinctive morning shifts were Puechabon (FR-Pue), Soroe (DK-Sor), and Loobos (NL-Loo). The framework that morning shifts are associated with water stress from soil moisture depletion would be supported by the increase in morning shifts during 2003, though factors such as species composition and access to soil water would play a significant factor and could account for the differences among sites. All sites which had significantly different ($p<0.05$, Wilcoxon rank-sum test) DWCI values between 2003 and all other years except Puechabon, whereas with C^*_{ET} only Puechabon, Soroe, and Loobos showed significant differences.

Furthermore, to highlight the divergent responses of the metrics between tree and grass dominated ecosystems, we have added a figure which shows the response of forest, savanna, and grassland C^*_{ET} and DWCI values binned by evaporative fraction (now Figure 5, here R2). In the figure, one can see the tendency for grassland sites to decouple under low evaporative fraction, while forest sites tend to show morning shifts, which ties into the discussion on tree vs grass responses and isohydricity.

Finally, we have added two new subplots to Figure 3 (now Figure 6 in the new manuscript, here (R3)), which in addition to current subplots showing the DWCI and C^*_{ET} response to LE by Rn and LE by GPP, shows the response to VPD by evaporative fraction (EF). These new subplots further differentiate the responses of the two metrics, as DWCI shows a combined effect of VPD and EF but C^*_{ET} only shows a response to EF and not VPD.

We hope these new plots, as well as the associated references to them in the results, give the reader a better understanding of the dynamics of the metrics and further support our subsequent Discussion section.

2. The authors claimed that they proposed two indicators. Are these indicators new and have not been used in the literature?

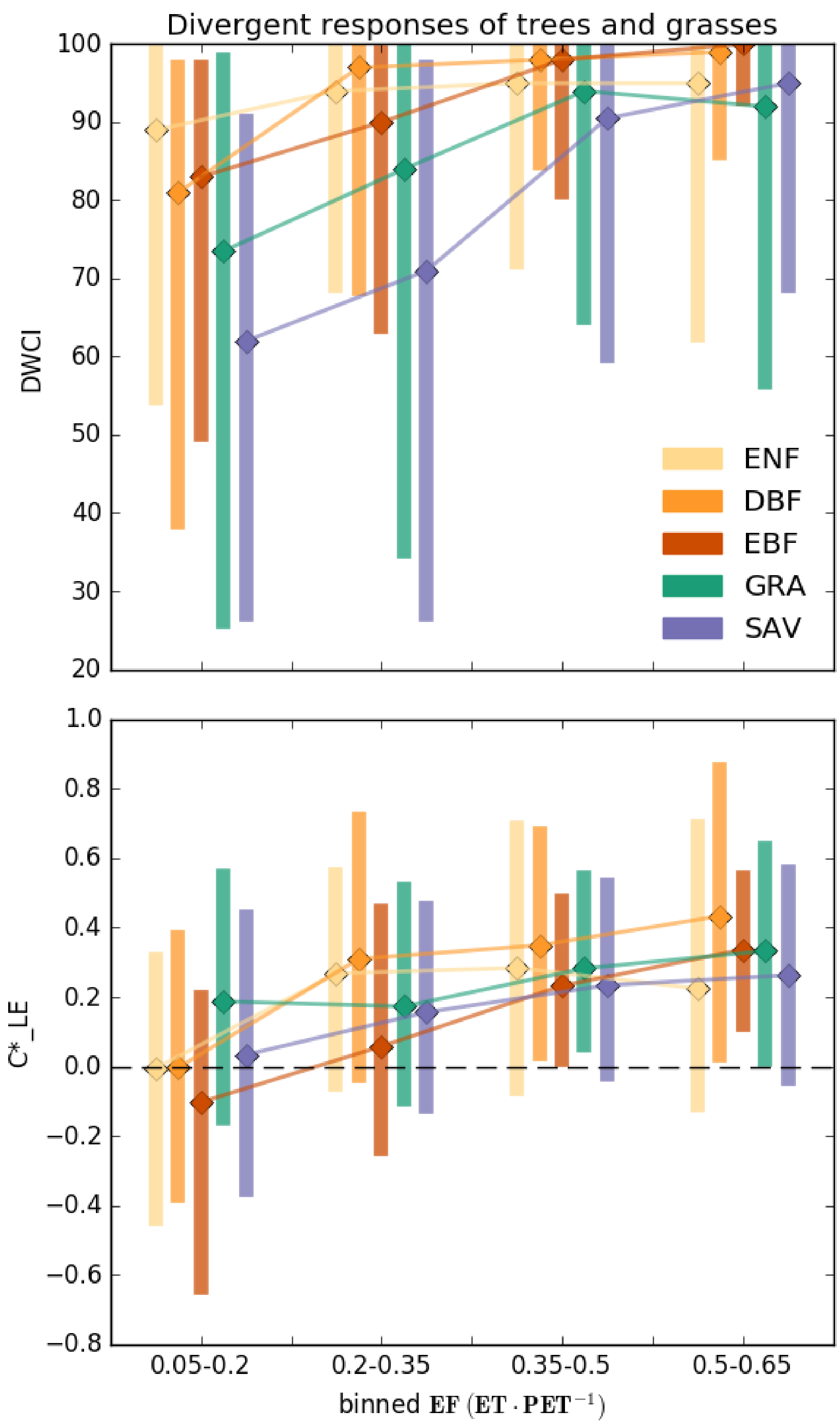

Figure R 2: Median diurnal water carbon index (DWCI, upper panel) and diurnal centroid (C^*_{ET}, lower panel) of plant flunctional types binned by evaporative Fraction (EF, low values indicate dry conditions). Note DWCI of 0-100 indicate lowest-highest probability of diurnal carbon:water coupling and C^*_{ET} of -1-1 indicate one hour morning shifted-one hour afternoon shifted ET. Evergreen needleleaf (ENF), deciduous broadleaf (DBF), and evergreen boradleaf (EBF) forests show increased morning shifts (low C^*_{ET}) with decreasing EF when compared to grassland (GRA) sites which tended to have decreased carbon:water decoupling (low DWCI) with decreasing EF. Savanna ecosystems (SAV) show a high degree of decoupling and intermediate levels of morning shifts. Vertical bars represent interquartile range.

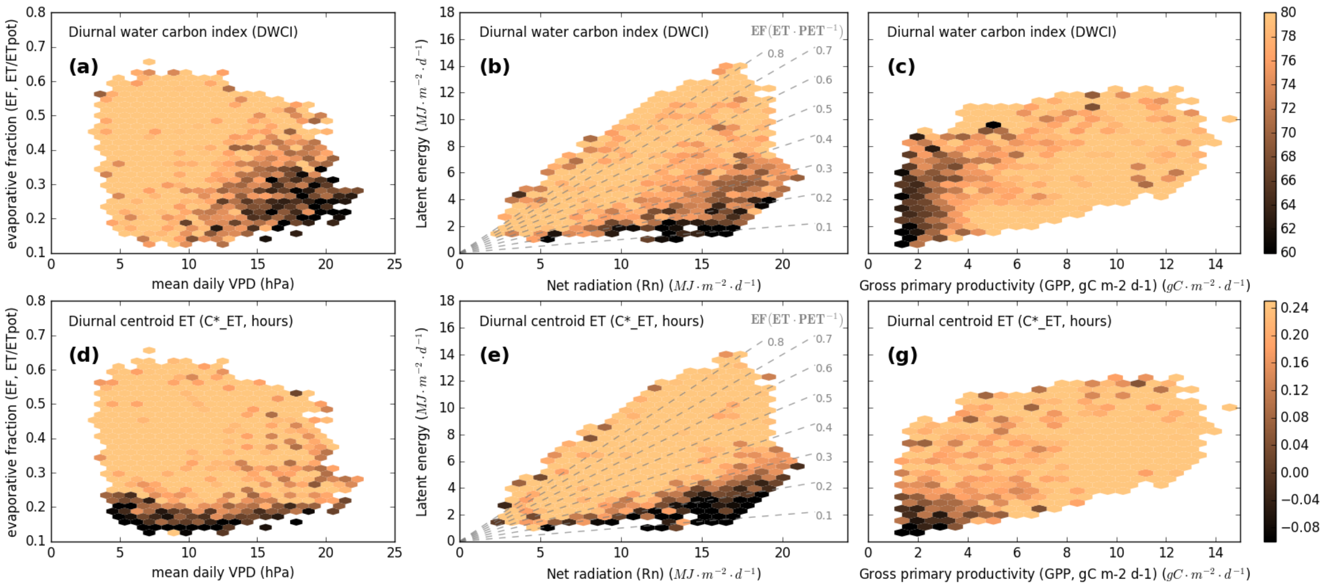

Figure R 3: Mean DWCI (upper panels) and C^*_{ET} (lower panels) with respect to evaporative fraction (EF) by vapor pressure deficit VPD (a,d), latent energy (LE) by Rn (b,e) and LE by GPP (c,g). Note DWCI of 0-100 indicate lowest-highest probability of diurnal carbon:water coupling and C^*_{ET} of -1-1 indicate one hour morning shifted-one hour afternoon shifted ET. Points with high Rn and low LE are associated with both low DWCI and C^*_{ET}, indicating that both metrics are related to water limitations. Though both metrics are associated with low EF, DWCI shows a much higher response to atmospheric demand as measured by VPD, with C^*_{ET} showing very limited response. Both metrics, and DWCI in particular, show low values with high ET and low Rn, though these points are also associated with over closed energy balances (LE+H>Rn-G). Both metrics are associated with low GPP, but the C^*_{ET} is restricted to both low GPP and ET, indicating water and carbon can decouple over a wider range of water stress. This also holds when points with energy balance over-closer are excluded (data not shown).

If they have been used in the literature, then they are not new and the authors should rephrase this statement. Take diurnal centroid as an example, it was used back in 2003 (Wilson et al. 2003), and what is new with the relative diurnal centroid?

The reviewer makes a good point that the relative diurnal centroid builds on the work of Wilson et al. [5] and should be properly credited. To this end the objectives have been amended to clarify that we propose these metrics particularly as indicators of water stress and now reads:

> To this end, we propose two data-driven indicators of water stress, the diurnal water:carbon index (DWCI) and the relative diurnal centroid in LE (C^*_{ET}).

We have also made the reference to Wilson et al. [5] more explicit, as well as highlighting the work of Matheny et al. [3] when introducing the metric:

> As soils dry, it becomes more difficult to transport stem and root zone moisture to the leaf, potentially causing hydraulic limitations for the plant to transport water. This shift was seen in eddy covariance data in a study by Wilson et al. [5], who examined the shift of latent compared to sensible heat, which suggested that a shift in water fluxes towards dawn can be indicative of afternoon stomatal closure. Shifts were further explored in a modeling study by Matheny et al. [3] which found that the morning shift was not well captured by models and attributed the errors to inadequate hydraulic limitations in the models. The daily cycle of wetting and drying acts as a capacitor in the hydraulic circuit, allowing water stores to be more easily transported in the morning and depleting in the afternoon. As bulk soil moisture declines, this effect may be strong enough to shift the diurnal cycle of ET significantly toward the morning. Quantifying diurnal shifts in EC data using the diurnal centroid was first explored by Wilson et al. [5]: defined as the flux weighted mean hour, or
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> $$C_{flux} = \frac{\sum flux_t \cdot t}{\sum flux_t}$$
>
> where t is a regular, sub-daily time interval.

Hopefully these changes give better context to the manuscript and proper credit to previous works.

3. The abstract should be rewritten to contain less introduction and more results.

The abstract has been rewritten to remove some introduction as well as to highlight the added analysis from the European heatwave in 2003:

> Understanding of terrestrial carbon and water cycles is currently hampered by an uncertainty in how to capture the large variety of plant responses to drought. In FLUXNET, the global network of CO2 and H2O flux observations, many sites do not uniformly report the ancillary variables

needed to study drought response physiology. To this end, we outline two data-driven indicators based on diurnal energy, water, and carbon flux patterns derived directly from the eddy covariance data and based on theorized physiological responses to hydraulic and non-stomatal limitations. Hydraulic limitations (i.e. intra-plant limitations to water movement) are proxied using the relative diurnal centroid (C^*_{ET}), which measures the degree to which the flux of evapotranspiration (ET) is shifted toward the morning. Non-stomatal limitations (e.g. inhibitions of biochemical reactions, Rubisco activity, and/or mesophyll conductance) are characterized by the Diurnal Water:Carbon Index (DWCI), which measures the degree of coupling between ET and gross primary productivity (GPP) within each day. As a proof of concept, the metrics indicated morning shifts and decoupling effects at 6 European sites during the 2003 heatwave event. Globally, we found indications of hydraulic limitations in the form of significantly high frequencies of morning shifted days in dry/Mediterranean climates and savanna/evergreen plant functional types (PFT), whereas high frequencies of decoupling were dominated by dry climates and grassland/savanna PFTs indicating a prevalence of non-stomatal limitations in these ecosystems. Overall, both the diurnal centroid and DWCI were associated with high net radiation and low latent energy typical of drought. Using three water use efficiency (WUE) models, we found the mean differences between expected and observed WUE to be -0.09 to 0.44 umol/mmol and -0.29 to -0.40 umol/mmol for decoupled and morning shifted days respectively compared to mean differences -1.41 to -1.42 umol/mmol in dry conditions. These results suggest that morning shifts/hydraulic responses are associated with an increase in WUE whereas decoupling/non-stomatal limitations are not.

4. The Introduction section is organized by sub-sections. The three levels of organization is pretty unusual for scientific papers. I suggest that the authors remove sub-section titles and rewrite it as a regular Introduction. If the authors intend to provide more background material, it is better to add a Background section right after the Introduction.

   Based on the reviewers suggestion, the sub-sections have been removed and the Introductions has been further shortened to be more focused on the subject at hand, such as removing the focus on transpiraiton estimates as suggested by reviewer 1 (comment 3), as well as removing discussion of the iWUE metrics which hopefully alleviates some unnecessary confusion.

5. It is unclear which FLUXNET database (LaThuile or 2015) is used in this study. Details should be provided. The Baldocchi et al. 2008 paper does not seem to be the proper citation for the database used. The supplementary figure can be moved to the manuscript given the relatively small number of illustrations.

   We agree that this was not made entirely clear and the reference was not the most appropriate one. We have updated our references to include the citation of the dataset pointing to the actual download location.

Further, as we have expanded the results section based on the reviewers suggestions, we have increased the number of figures from 5 to 7, with an additional supplementary figure showing a sensitivity analysis of the metrics to GPP and air temperature, as well as sensitivity of the frequency decoupled and morning shifted days based on different thresholds.

6. Line 30, page 4: FileS1 is a nice way to present study sites. Adding some technical details about how this kind of file was created will be helpful to the audience who might want to produce this kind of illustration as well.

   We are glad the reviewer likes our presentation of the sites. The file is created using the Bokeh package in Python based on the following technical example: https://bokeh.pydata.org/en/latest/docs/user_guide/geo.html. A reference to this example has been added to File S1, hopefully allowing these types of presentations to be more commonplace in literature.

7. Figure 2: An overall title should be added for the figure. Moreover, "upper" and "lower" should be changed to something like "Upper panels:" and "Lower panels:", respectively.

   We have given this figure the overall title of "Theoretical overview of diurnal water carbon index" and the upper and lower designations have been changed as the reviewer suggested. This designation was also used in the new figures (now figures 3 (R1) and 5 (R2))

8. Line 8, page 3: "are GPP" should be changed to "GPP are".

   This has been corrected.

9. Line 25, page 8: remove "be".

   This has been corrected.

References

[1] Ph. Ciais et al. "Europe-wide reduction in primary productivity caused by the heat and drought in 2003". en. In: *Nature* 437.7058 (Sept. 2005), pp. 529–533. ISSN: 0028-0836, 1476-4687. DOI: 10.1038/nature03972. URL: http://www.nature.com/articles/nature03972 (visited on 01/16/2018).

[2] A. Granier et al. "Evidence for soil water control on carbon and water dynamics in European forests during the extremely dry year: 2003". en. In: *Agricultural and Forest Meteorology* 143.1-2 (Mar. 2007), pp. 123–145. ISSN: 01681923. DOI: 10.1016/j.agrformet.2006.12.004. URL: http://linkinghub.elsevier.com/retrieve/pii/S0168192306003911 (visited on 01/16/2018).

[3] Ashley M. Matheny et al. “Characterizing the diurnal patterns of errors in the prediction of evapotranspiration by several land-surface models: An NACP analysis: Error patterns in modeled transpiration”. en. In: *Journal of Geophysical Research: Biogeosciences* 119.7 (July 2014), pp. 1458–1473. ISSN: 21698953. DOI: 10.1002/2014JG002623. URL: http://doi.wiley.com/10.1002/2014JG002623 (visited on 02/15/2016).

[4] M. Reichstein et al. “Reduction of ecosystem productivity and respiration during the European summer 2003 climate anomaly: a joint flux tower, remote sensing and modelling analysis”. en. In: *Global Change Biology* 13.3 (Mar. 2007), pp. 634–651. ISSN: 1354-1013, 1365-2486. DOI: 10.1111/j.1365-2486.2006.01224.x. URL: http://doi.wiley.com/10.1111/j.1365-2486.2006.01224.x (visited on 01/16/2018).

[5] Kell B. Wilson et al. “Diurnal centroid of ecosystem energy and carbon fluxes at FLUXNET sites: DIURNAL ENERGY FLUXES AT FLUXNET SITES”. en. In: *Journal of Geophysical Research: Atmospheres* 108.D21 (Nov. 2003). ISSN: 01480227. DOI: 10.1029/2001JD001349. URL: http://doi.wiley.com/10.1029/2001JD001349 (visited on 06/13/2016).