Interactive comment on "Response of water use efficiency to summer drought in boreal Scots pine forests in Finland" by Yao Gao et al.

We deeply appreciate all the reviewers for their constructive comments in improving the scientific quality of this manuscript. Our point-by-point response to all the reviewers' comments are listed below, and corresponding modifications are also made for the manuscript. We hope our reply will satisfy the expectations from reviewers.

Response to Anonymous Referee #1

General comments:

This paper deals with an important issue relating the water and carbon cycles on the ecosystem level. The authors used two long-term datasets and derived interesting results about water use efficiency.

The introduction is good, explaining well the problem and citing many recent references. The methodology describes well the sites characteristics and the methods used.

Finally, the text is well written and the quality of figures is good.

Specific comments:

Abstract Lines 16-17: It would be better to have a sentence or two explaining how EWUE and IWUE were defined, since different definitions might be used such as NEE/ET for EWUE.

Authors response (AR): The explanations of how EWUE and IWUE were defined have been added.

Line 74: IWUE is mentioned but not defined. It is defined later in the text, but it helps the reader to understand of is being described at this point.

AR: The definition of IWUE has been given at this point in the text.

Response to Anonymous Referee #2

General comments :

In their paper *Response of water use efficiency to summer drought in boreal Scots pine forests in Finland* Gao et al. address a timely problem in biogeochemistry, the interaction of the carbon with the water cycles. Knowledge of this relationship is particularly uncertain during periods of water stress, for which the exact physiological mechanisms and their ecological variability are unknown.

Nevertheless, I have the following major comments that I think should be addressed:

1. The authors should discuss why IWUE was chosen as a metric in addition to WUE. A recent study (Zhou et al. 2015) demonstrated that a definition based on a square-root relationship with VPD is superior to the definition of Beer et al. (2009). Notably, the latter is already expected to be dependent on VPD, as stomata react to this variable and thus the surface conductance changes accordingly.

AR: In the revised paper, we added the underlying water use efficiency (uWUE) that introduced by Zhou et al. (2014) for a comparison with WUE and IWUE for studying their performances during the summer drought. IWUE is defined as WUE multiplied with mean daylight vapor pressure deficit (VPD), and it has been found to increase during short-term moderate drought. In the formulation of IWUE, ET/VPD is a hydrological measure of the surface conductance at the ecosystem level (Beer et al., 2009). The uWUE is proposed based on IWUE and a simple stomatal model of Lloyd and Farquhar (1994). Different to IWUE which is still affected by the nonlinear effect of VPD, the uWUE has been found to represent the best linear relationship among GPP, ET and VPD at the half-hourly time scale by Zhou et al. (2014). Later on, the appropriateness of uWUE at daily time scale has been demonstrated (Zhou et al., 2015). However, we were not clear how uWUE behaves during drought period. In our study, we found that uWUE doesnot show a change during the short-term summer drought at our site. As uWUE is more independent of VPD, it is considered that uWUE is more suitable as a plant functioning metric to evaluate the impact of global change on plant functioning at ecosystem level in the long term. Those contents have been introduced and discussed in the revised manuscript.

2. Lines 184-190 address the problem of soil evaporation. While it is true that model predictions of transpiration can be used as proxy variable, this comes at the cost of additional model uncertainties. The cited paper of Beer et al. (2009), which establishes the concept of IWUE, tries to circumvent this problem by excluding days following precipitation events. Most of the excluded days would lie outside dry spells, hence retaining sufficient sample size for these periods. The data presented in the current manuscript could be filtered according to such a criterion; then it would be important to see whether the observed patterns persist or change in magnitude. Generally this approach would be more robust than basing the IWUEt/EWUEt estimates on a model with known deficiencies.

AR: Yes, we filtered our data to exclude the rainy days and the certain amount of dry days after the rainy days in the revised manuscript. As suspected by the reviewer, sufficient sample size for the drought period retain after the data selection. We could observe a more significant pattern of the impacts on GPP and ET from the soil moisture drought.

3. I think it is questionable that daily averages were used for the analyses. Especially in light of problems such as dew-fall it would make sense to use day-night-time separated data for the analyses. At least, the absence of day-night-time separation should be mentioned in the text.

AR: The data has now been reprocessed for the analysis, and only daytime data without precipitation influence were selected. The data selection process is described in section 2.2. In the revised manuscript, only half-hourly data with shortwave radiation (Rs) larger than 100 W/m^2 were selected for the aim to select the effective time for plant photosynthesis. The rainy days and certain amount of dry days after the rainy days were also excluded. By doing this, data with negative GPP and ET were excluded.

4. Regarding the effect of atmospheric humidity the text states that "Our results indicate that the combined effects of soil moisture and atmospheric drought on stomatal conductance have to be taken into account." (ll.351-353) I think the current version of the text doesn't fully establish the interaction and correlation between the atmospheric and subsurface stress factors. The observed effects by themselves are not unexpected, as the model in its current form simply lacks the stomatal response to atmospheric humidity.

AR: Yes, the model in its current form lacks the stomatal response to atmospheric humidity. In global ecosystem models, simple representations of stomatal regulation have often been applied to reduce

computing costs. Because VPD and soil moisture are to certain degree correlated, inclusion of one of the either has often shown to be enough to account for drought effects. In the revised manuscript, the formulations of the default stomatal conductance model in JSBACH has been added. It can be found that the soil moisture condition is the only limiting factor in the default stomatal conductance model in JSBACH. Knauer et al. (2015) tested a few stomatal conductance models in the JSBACH model under non-limited soil moisture conditions, and the results showed that Ball-Berry model (Ball et al., 1987) to be best in its response to atmospheric drought. However, the performance of the default stomatal conductance model under limited soil moisture conditions has not been tested before this study. Our results showed that the model can successfully capture the turning point of GPP and ET when the SMI decreased to be lower than 0.2. However, the decreases of GPP and ET are not as strong as in the observations. Thus, our results indicate that the combined effects of soil moisture and atmospheric drought on stomatal conductance have to be both taken into account. Even though no such a correlation between the stress factors was established in our study, it was demonstrated that at certain point the correlation between GPP or ET and soil moisture or VPD vanishes. So it is insufficient to use only soil moisture or VPD to describe drought stress.

5. The paragraph in ll.325-329 is confusing. First, the statement that "This means that the intrinsic water use efficiency at the ecosystem level is enhanced during soil moisture drought." is merely restating the increase already mentioned in the preceding sentence. Further, wouldn't one expect that a better adaptation to drought leads to elevated IWUE, rather than interpreting a constant IWUE as the sign for this adaptation? Aside from that, it could be worth commenting on whether differences in adaption between the southern and northern site would be expected *a priori*, e.g. due to average recurrence times of droughts at these locations.

AR: Yes, we agree with the reviewer the sentence is redundant and we have revised this paragraph. However, we do not agree with reviewer on the assumption that elevated IWUE would necessarily be a sign of adaptation. The trees might also be opportunistic in their strategies. The different behaviors of IWUEs imply different strategies in the south than in the north.

6. Generally, the inclusion and evaluation of JSBACH simulations would profit from a more targeted motivation. What is the predicted behavior? What is already known? In what way could the presented analysis contribute to an improvement of the model? In addition to that, the formulation used for the effect of soil moisture on stomatal conductance should be stated.

AR: For our reply to the first part of this comment, please refer to our answer for the comment 4 above. Additionally, we have added a section 2.3.1 in the revised manuscript to describe the stomatal conductance model in JSBACH.

Specific & minor comments:

- The authors state correctly that "there may be systematic errors source from imperfect spectral corrections and gap-filling procedures or calibration problems" (ll.364-365). This would make it all the more important to report which exact criteria were used to exclude observations with insufficient data quality.

- l.109: Which partitioning method was used? Should be mentioned and cited in the text.

AR: For Hyytiälä, EC fluxes were calculated using standard methods as described in Mammarella et al (2016). Data quality of 30 min values of NEE and latent heat flux (LE) was ensured excluding records

with low turbulent mixing (friction velocity below 0.25 m/s) as described in Markkanen et al. (2001), Mammarella et al (2007) and Ilvesniemi et al. (2010). The NEE was partitioned into Re and GPP according to Kolari et al. (2009). Shortly, Re was modelled using an exponential equation with temperature at a depth of 2 cm in the soil organic layer as the explanatory factor. The value of GPP was then directly derived as residual from the measured NEE. When NEE was missing, GPP was estimated according to Eq.7 in Kolari et al. (2009). LE was gap-filled using a linear regression against net radiation in a moving window of 5 days. Then ET is converted from LE. We have added these details and the missing references in the revised manuscript.

Kolari, P., Kulmala, L., Pumpanen, J., Launiainen, S., Ilvesniemi, H., Hari, P., and Nikinmaa, E.: CO2 exchange and component CO2 fluxes of a boreal Scots pine forest, Boreal Environment Research, 14, 761- 783, 2009.

Mammarella, I., Peltola, O., Nordbo, A., Järvi, L., and Rannik, Ü.: Quantifying the uncertainty of eddy covariance fluxes due to the use of different software packages and combinations of processing steps in two contrasting ecosystems, Atmos. Meas. Tech., 9, 4915-4933, doi:10.5194/amt-9-4915-2016, 2016.

Markkanen, T., Rannik, U., Keronen, P., Suni, T., and Vesala, T.: Eddy covariance fluxes over a boreal Scots pine forest, Boreal Environment Research, 6, 65-78, 2001.

Ilvesniemi, H., Pumpanen, J., Duursma, R., Hari, P., Keronen, P., Kolari, P., Kulmala, M., Mammarella, I., Nikinmaa, E., Rannik, U., Pohja, T., Siivola, E., and Vesala, T.: Water balance of a boreal Scots pine forest, Boreal Environment Research, 15, 375-396. 2010.

Mammarella, I., Kolari, P., Rinne, J., Keronen, P., Pumpanen, J. and Vesala, T.: Determining the contribution of vertical advection to the net ecosystem exchange at Hyytiälä forest, Finland, Tellus B, 59, 900-909, doi:10.1111/j.1600-0889.2007.00306.x, 2007.

- ll.379-381: "Also, in the relationships between ET/T and VPD at the two sites, both observed and simulated ET/T showed a small decrease under moderate soil moisture drought, compared to days with higher soil moisture conditions." It is not clear from this sentence, whether this relates to the sensitivity of ET to VPD or ET itself.

AR: We agree with the reviewer that the sentence is not clear enough. It was referred to the sensitivity of ET to VPD. We have revised this part also because the data was reprocessed for the revised manuscript.

- The limitations of the EC method mentioned in ll.361-365 are true by itself, however in the current text they appear very unconnected to any discrepancies or problems in the analyses. If specific problems of the method, such as the energy-balance-closure- gap can be made responsible for particular deviations, that should be connected in the discussion. Else, the part can be shortened and moved to the methods section.

AR: Yes, we will move this part to the methods section in the revised manuscript.

Technical corrections :

- "In addition, there may be systematic errors source from imperfect spectral corrections and gap-filling procedures or calibration problems" (ll.364-365) should be changed to "In addition, imperfect spectral corrections and gap-filling procedures as well as calibration problems may be sources of systematic errors."

AR: *We did the change as reviewer suggested.*

Citations
Zhou et al. (2015). Daily underlying water use efficiency for AmeriFlux sites. *Journal of Geophysical Research: Biogeosciences*. DOI: 10.1002/2015JG002947.

Response to Anonymous Referee #3

Currently, global carbon and water cycles as well as the associated carbon-water coupling relationships are receiving more and more attentions in this research field. Particularly under the changing climate, how extreme climate events affect the carbon sequestration of terrestrial forests directly related to the future climate projections. This study aimed to reveal the responses of ecosystem water-use efficiency to summer drought in northern Europe, which will also enrich this hot topic. The work is well organized with clear structure. However, plenty of questions still need to be solved.

Major comments:

1. In the part of "Introduction", the authors used a lot of sentences associated with ecosystem water-use efficiency, such as WUE, EWUE, and IWUE. Moreover, they want to express the potential effects of drought on different WUE expressions. I strongly suggest the authors to explain the differences of various WUE definitions, and the reasons adopted in the present study. Then, the authors used many phrases to describe soil water status. However, it is crucial that how do they define the droughts, especially severe or moderate.

AR: *The definitions and background of those WUE metrics have been given in the revised introduction. In the revised manuscript, we use the soil moisture index (SMI) to describe the soil moisture status rather than the different droughts at the study site. Thus, in the revised manuscript, the soil moisture conditions were classified into five SMI groups with an interval of 0.2: very dry: $0 \leq SMI < 0.2$, moderate dry: $0.2 \leq SMI < 0.4$, mid-range: $0.4 \leq SMI < 0.6$, moderate wet: $0.6 \leq SMI < 0.8$, very wet: $0.8 \leq SMI < 1$.*

2. In the part of "2.5 Soil Moisture Index (SMI)", the authors used SMI derived from simulated soil moisture and soil parameters in JSBACH to define soil moisture conditions. It may lead to the uncertainty owing to the model performance and the results in this study. Then, why not validate the accuracy of the modeled data. The SMI results are also classified as severe drought, moderate drought, mid-range, moderate wet and very wet. However, only 11-year dataset for Hyytiala and 8-year dataset for Sodankyla, which may be not enough for drought analyses.

AR: *In section 3.1 of the revised manuscript, the simulated SMI that is calculated with simulated soil moisture and soil parameters in JSBACH has been compared with the observed SMI based on observed soil moisture and measured soil parameters. The simulated SMI agreed well with in situ observed SMI over the 11-year study period, with a correlation coefficient (0.625) and a root-mean-square error (RMSE) of 0.225. Moreover, a very good time correlation (0.965) between simulated and observed SMIs were found for year 2006, despite the simulated SMI is systematically lower than the observed*

SMI (RMSE = 0.12). As we have answered to the above major comment from reviewer #3, the five SMI groups were renamed to represent different soil moisture conditions rather than drought conditions. Unfortunately, we have used the entire data period of the measured soil moisture at the sites. However, Muukkonen et al. (2015) showed that the summer drought in 2006 has caused severe forest damages in southern Finland. Using SMI calculated from regional soil moisture simulations over the past 30 years (1981-2010), such extreme drought affecting forest health has been illustrated to be rare in Finland, and the summer drought in 2006 was the most severe one in the 30-year study period (Gao et al., 2016). In the revised manuscript, we had more detailed analysis of the severe summer drought in 2006 at Hyytiälä, and the Sodankylä site was not included in the paper anymore due to no such severe soil moisture drought in the study period.

3. In the part of "Results and Conclusion", the authors concluded that based on observed data, the ecosystem level water use efficiency (EWUE) showed a decrease only during a severe soil moisture drought at Hyytiälä, whereas the inherent water use efficiency (IWUE) increased when there was a severe soil moisture drought at Hyytiälä and a moderate soil moisture drought at Sodankylä. However, on one hand, this study is based on "no severe soil moisture deficit at Sodankylä during the study period", on the other hand, it seems to be a lack of persuasion. Maybe more data need to be supplemented to enrich the objectives of this study.

AR: Yes, we agree with the reviewer that sentence was a bit misleading because there was no such severe drought at Sodankylä during the study period. Please also see the answer to the previous comment.

4. In the part of "Discussion", I suggest the authors to supplement the uncertainties of SMI, which is used as drought indicator of soil water. In addition, a lot of biotic and abiotic factors controls the differences of GPP, ET, WUE of the two forest sites. So, how do they directly compare the effects of drought on Scots pine forest under different local environmental conditions. Apart from this, I think in northern Europe such as Finland, temperature anomaly may be more sensitive than drought.

AR: As answered to the comment 1, we realized that it is inappropriate to use fixed SMI groups to describe different drought conditions. However, SMI that ranges from 0 to 1 describes the status of soil moisture available to plants. How to divide the groups of SMI is a matter of choice. In the revised manuscript, we grouped SMI with an interval of 0.2 to reflect different soil moisture status: very dry: $0 \le SMI < 0.2$, moderate dry: $0.2 \le SMI < 0.4$, mid-range: $0.4 \le SMI < 0.6$, moderate wet: $0.6 \le SMI < 0.8$, very wet: $0.8 \le SMI < 1$.

We also agree with the reviewer's opinion that it is a bit uncertain to draw the conclusion about the comparison between the southern site and northern site (scots pine has weaker response to drought in the southern site than in the northern site) by analysing current available data, especially there is no severe soil moisture drought in the studied period in the northern site. Therefore, in the revised manuscript, we focused on the drought event and its impact on plant functioning in the southern site.

Minor comments:

1. P1 L13 & L23 "at daily time scales" should be changed to "at the daily time scale".

AR: We did the change as reviewer suggested.

2. L15-L18 This long sentence is too tedious. Please reconstruct it.

AR: The sentence has been reformulated according to the revised results.

3. P2 L37 Terrestrial plants assimilate carbon dioxide (CO2)...

AR: We did the change according to this comment in revised manuscript.

4. L59 EWUE is broadly adopted as a surrogate for WUE due to data availability. Why? This expression is abrupt without explanation.

AR: The sentence has been reformulated as: "EWUE is broadly adopted as a surrogate for the leaf level WUE because more data are available at the ecosystem level than at the leaf level.".

5. L65 It is inappropriate to cite the paper of Reichstein et al. 2002. Ecosystem water-use efficiency of gross carbon uptake decreased during the drought, regardless whether evapotranspiration from eddy covariance or transpiration from sapflow had been used for the calculation.

AR: Indeed, the reference was misused. we deleted this reference in the revised manuscript.

6. P3L90 Lack of the information on forest ages between the two flux sites.

AR: We have given the forest age information in the revised manuscript.

7. P4L112 "For our analysis, daily values of GPP and ET fluxes were calculated as daily sums of half-hourly values and only good quality gap-filled data were used." It is confusing. How do they guarantee the comparability of different days?

AR: The original sentence was confusing and not total correct. It has been deleted in the revised manuscript. Actually, the bad quality data was also gap-filled, and the gap-filled data were used. The gap filling method for GPP and ET was introduced in the manuscript. Thus there is no problem with the comparability of different days.

8. P4L131 Grammar mistakes. "The models of Farquhar et al. (1980) is used for photosynthesis of C3 plants."

AR: We have corrected the sentence to be " The models of Farquhar et al. (1980) and Collatz et al. (1992) is used for photosynthesis of C3 and C4 plants, respectively."

9. P6L188 "However, process-based ecosystem models can be used to reveal plant physiological processes by separating evaporation and transpiration." Please cite the associated references.

AR: This sentence should be reworded as: "However, process-based ecosystem models do resolve evaporation and transpiration, which together composing evapotranspiration". We do not think a reference is needed after reformulation.

10. P9L311 "The consequence of decreased ET due to soil moisture drought would be increased atmospheric VPD, which in turn accelerates stomatal closure..." Please reconstruct it.

AR: We have reworded the sentence as "The decrease of ET due to soil moisture drought could lead to

increased atmospheric VPD, which in turn intensifies stomatal closure ..."

11. Please specify the time scale of data used in the figures. In addition, the data points are too dense. It is hard to extract useful information from the merged figures.

AR: The time scale of data (the averaging period and the study period) has been added in the figures. As the data has been reprocessed in the revised manuscript to exclude rainy days and certain amount of dry days after the rainy days, the amount of data shown on the figures has been reduced. The figures have been reselected and composed in the revised manuscript. We think it should be OK to extract useful information from figures in the revised manuscript.

12. In Figure 4, many values of WUE at the daily time scale exceed 10 g C kg-1 H2O, especially for simulated results of EWUE and IWUE. Do you think it is rational or just statistical?

AR: It was quite statistical due to the small ET values, which are mainly impacted by rainy days and days after rainy days with high atmospheric humidity, as well as night time condensation effect. In the revised manuscript, the data has been reprocessed to exclude precipitation and night time impacts on GPP and ET. Thus, there are only three days with EWUE values larger than $10\ g\ C\ kg^{-1}\ H_2O$ for the simulated results in the updated figure, and no EWUE values are larger than $10\ g\ C\ kg^{-1}\ H_2O$ for the observed results.

Response to Anonymous Referee #4

The article presents an analysis of GPP, ET and water use efficiency metrics for two flux-towers in Finland in search for drought effects or more generally for soil moisture controls on the carbon and water fluxes. The climate and hydrological regime of these sites restrain appreciable effects of water limitations on GPP, ET and water use efficiency to few days during summer 2006 in the southern site of Hyytiälä (Line 210, Line 241-242, Fig.1 and 3) This is probably the most interesting result of the article but constrains quite significantly the scope of the analysis. The data analysis in Fig. 2 is interesting in certain aspects, but overall, the study leaves me quite doubtful about its novelty in the presented conclusions (see comments below). The link between soil moisture and plant physiologically meaningful thresholds is also very weak. A land surface model, JSBACH, is also used to reproduce the water and carbon fluxes but serious model limitations, a relatively weak rationale for using the model, and a poor model-data comparison make this part insufficient.

Major comments:

1) I struggle to identify the novel conclusions of the manuscript (beyond the presentation of the data themselves). The main conclusions are: (i) There are only few days of water limitations in only one of the two analyzed sites despite the 11 and 8 years of analyzed data. Interesting result but it partially hampers the scope of the article. (ii) IWUE and EWUE are identifying two different aspects of ecosystem response, with the first more appropriate to capture changes in surface conductance. This is of course important but it is expected too because one depends explicitly on VPD and the other does not. (ii) Ecosystem models, in this case JSBACH, need to have a very good representation of stomatal functioning and its dependence with VPD or humidity, which is known since quite some time (Ball et al 1987, Leuning 1995) and widely debated in literature (e.g., Monteith 1995; Damour et al 2010) and actually included in most of the models.

AR: (i) We have revised the manuscript to only focus on the severe drought in 2006 at Hyytiälä site,

because no severe drought took place during the multi-year study period at the northern Sodankylä site. The summer drought in 2006 caused severe forest damages in southern Finland (Muukkonen et al., 2015). Using SMI calculated from regional soil moisture simulations over the past 30 years (1981-2010), such extreme drought affecting forest health has been illustrated to be rare and the summer drought in 2006 in southern Finland was the most severe one in the 30-year study period (Gao et al., 2016). Therefore, it is valuable to study the severe drought in 2006 and its impact on plant functioning.

(ii) We aimed to compare the behavior of different water use efficiency metrics under the soil moisture drought. From the literature presented in introduction, we have understood that there is no clear conclusion of the impact of drought on EWUE (increase or decrease), and therefore it is valuable to study the performance of EWUE in drought conditions, as it is widely used metric describing ecosystem level responses. IWUE is a quantity defined as EWUE multiplied with mean daylight vapor pressure deficit and has been found to increase during short-term moderate drought (Beer et al., 2009). In the revised manuscript, we also added uWUE which is developed based on IWUE and a simple stomatal model, to more explicitly assess the role of the stomatal conductance, and to see how uWUE behaves in comparison to the two other metrics.

(iii) We agree that it is ideal that ecosystem models can have a very good representation of stomatal functioning and its dependence on VPD. However, in global ecosystem models, simple representations of stomatal regulation have often been applied to reduce computing costs. Because VPD and soil moisture are to certain degree correlated, inclusion of one of the either has often shown to be enough to account for drought effects. In the revised manuscript, the formulations of the default stomatal conductance model in JSBACH has been added. It can be found that the soil moisture condition is the only limiting factor in the default stomatal conductance model in JSBACH. Knauer et al. (2015) tested a few stomatal conductance models in the JSBACH model, and the results showed that Ball-Berry model (Ball et al., 1987) to be best in its response to atmospheric drought under non-limited soil moisture conditions. However, the performance of the default stomatal conductance model under limited soil moisture conditions has not been tested before this study. Our results indicate that the combined effects of soil moisture and atmospheric drought on stomatal conductance have to be both taken into account.

2) In my opinion, the use of model simulations in the article lacks a clear rationale. The model is simply used to run the same period of observations and to reproduce the same variables which are observed (only transpiration and EWUEt, IWUEt are additionally analyzed). Therefore, there is not really a benefit or the idea to use the model for specific numerical experiments that go beyond observations. If the scope is confined to test the model performance only, also in this case there is not a direct comparison with data. No scatter plot to evaluate magnitude, seasonality, or other aspects of model performance is shown. Even the behavior with respect to the driving variables (Rsw, Ta, VPD and an index of soil moisture) is shown only qualitatively and not quantitatively, since the simulated and observed variables are never presented in the same plot (Fig. 2, 3, 4).

AR: The purpose of our study are twofold: one is to find how drought influences plant functioning using observational data; the other one is to see if the model can represent the drought and its impact on plant functioning in line with the observational data. In the revised manuscript (section 3.1), the observed SMI and simulated SMI were compared during the study period and drought year. We agree that the GPP and ET changes with respect to the driving variables show how the modelled GPP and ET perform qualitatively, but this (i.e. how modelled GPP and ET changes due to the drought) is what we are mostly interested in. We also think showing how the GPP and ET values differ under different environmental conditions, provide even more useful information for the model improvements than what

we can get from correlations by plotting data in the same figure.

3) I also have doubts about the choice of the model. From the manuscript description, JSBACH has only few layers of soils, which do not allow a proper representation of soil moisture vertical dynamics (Line 237-240) and most importantly, there is no representation of vegetation physiology with regards to water stress (thresholds for stomatal closure or plant vital functions), or at least this is not described in the article. Water content limits rather than more physiologically meaningful water potentials are used, which leaves the doubt if the selected thresholds have any meaning for the plant response to drought or not (e.g., Hsiao 1976).

AR: Most global land surface models have few layers of soil due to the limitations in computational costs. Nevertheless, drawn from Gao et al. (2016), we can conclude that regionally the model provides relatively robust estimate of SMI. In the revised manuscript section 3.1, good correlation coefficients were found between the simulated SMI and observed SMI over the study period and especially in the drought year. Moreover, there is parameterization of response of vegetation physiology on drought. We have added the formulations of stomatal conductance model in JSBACH as section 2.3.1. Furthermore, the thresholds are evenly set in terms of SMI. SMI is an indicator of soil moisture drought but not the physiological drought. We work more in the meteorological terms than in the plant physiological terms. The deviating responses among different SMI groups as functions of meteorological drivers reflect the response of vegetation. We agree that the original names for the SMI groups easily led to confusion about soil moisture drought or plant physiology drought. Thus, we renamed the SMI groups to describe the soil moisture conditions as very dry, moderate dry, mid-range, moderate wet and very wet.

4) The manuscript is generally decently written but there are parts, (e.g., abstract, introduction) which can be written much better (see minor comments below). Also the choice of the presented material is debatable. For instance, Sodankylä is one of the two presented case studies but nothing about Sodankylä is graphically presented in the main manuscript. Data uncertainty issues are discussed but not represented. Different figures share the same information; those can be better re-organized to highlight some of the main conclusion, which are not so evident from the current Figures (e.g., Line 325-326).

AR: We have tried to solve those minor comments below and rewrite parts of the paper. We revised the paper to focus on the severe drought at Hyytiälä site. The Sodankylä site is not included in the analysis anymore as there is no severe drought happened at Sodankylä in the study period. Figures were reselected and recomposed in the revised manuscript.

Specific comments:

Page 1. Line 11. I respectfully disagree with this statement; we have a good knowledge and wide body of literature about the carbon and water coupling, from stomatal level to ecosystems (e.g., Katul et al 2012). What it is still problematic is the modeling of the response of vegetation to periods of water stress at different temporal scales (from hourly to multiannual) and at different spatial scale (from a single tree to a region).

AR: We tried to simplify this introductory sentence to be: "The influence of drought on plant functioning has received considerable attention in recent years, although our understanding of the response of carbon and water coupling to drought in terrestrial ecosystems still needs to be improved.".

Page 1. Line 18-20. This sentence is very badly phrased, what does exactly mean that the decrease in ET is alleviated by increased VPD? If a decrease in ET is observed, this is already implicitly account for changes in VPD. The authors are here referring to the difference between EWUE and IWUE, with the first affected by VPD, why the latter is independent and therefore more indicative of how surface conductance changes. This is, however, not clear from the text.

AR: We wanted to mean that the decrease in stomatal conductance can lead to decreased Transpiration, and low soil moisture can lead to decreased Evaporation. However, as the VPD also increases during the soil moisture drought, the increased VPD could stimulates ET to a certain degree. In general, the ET still decreased during soil moisture drought. We have reformulated this part in the revised manuscript.

Page 1. Line 25. What do the authors mean with "deviated groups"? This is explained only much later in the manuscript. I am not a native speaker but the use of the term "deviated groups" appear, at the very least, awkward to me.

AR: The "deviated groups" there referred to the group of data under the severe soil moisture drought. We have deleted this term in the revised manuscript.

Page 2. Line 42. It is not very clear what the authors mean with "physiological stress" but if they refer to impairment of vital functions and plant mortality, I think that physiological stress may occur much later (at much higher levels of water stress) than reduced carbon uptake.

AR: Yes, we agree the physiological stress may occur at higher levels of water stress when plant starves as a result of continued metabolic demand for carbohydrates. Therefore, we have revised the sentence as: "... which in turn leads to less carbon uptake (diffusion of CO_2 into the leaf) and maybe also subsequent physiological stress …".

Page 2. Line 46. I think this sentence could be written much better in English.

AR: We have reformulated the sentence as: "Even though the occurrence of drought is low in northern Europe, the summer of 2006 in Finland has been found to be extremely dry and 24.4 % of the 603 forest health observation sites over entire Finland showed drought damage symptoms in visual examination, in comparison to 2–4 % damaged sites in a normal year (Muukkonen et al. 2015)."

Page 2. Line 54-55. This sentence is overly approximate. Ecosystem functioning depends on many more factors than WUE (e.g., nutrient dynamics, species competition and forest demography, just to quote some) and WUE is not simply "closely related" to water and carbon cycles but it is the metric which summarizes how the two cycles are coupled, at least at the flux-level.

AR: We agree with the reviewer. We have reformulated the sentence as: "WUE can be used to study ecosystem functioning which is closely related to the global cycles of water, energy and carbon."

Page 2. Line 62-73. I think many of these contrasting results can be simply related to the fact that a water-stress, which is perceived by the plants, occurs or not.

AR: We do not fully agree with the reviewer about this comment. We think the plants do perceive water stress if such conditions have been reported in those studies. Whether the plants react to water stress and how they react to it, depends on the severity of drought, and also other factors such as species (leaf

properties, canopy architecture, rooting depth etc) and plants' adaptation to the local climate.

Page 3. Line 96. I wonder if the choice of reporting LAI as "all-sided" rather than as "one-side/projected" as typically done in most of the literature (including for the very same sites, Lindroth et al 2008) is a good choice or not. At the very least, this should be clarified in the text and not only on the Table.

AR: We have clarified this in the text.

Page 4. Line 113-114. This sentence is not very clear to me. How do you distinguish between filled data of "good-quality" and "bad-quality"? Do you mean that that you discard days with observed low-quality data? Do you mean that you gap fill these data? Do you mean that you discard "half-hourly" periods and you average the others?

AR: We agree the original sentence was confusing and not totally correct. It has been deleted in the revised manuscript. Actually, the bad quality data was gap-filled, and the gap-filled data were used for averages. The gap filling method for GPP and ET was introduced in the manuscript.

Section 2.3. I know that JSBACH is an established model, but the model description is extremely synthetic. I would invite the authors to add a bit more of information. For instance, there is no mention of how the hydrological budget is solved. How do JSBACH deal with transpiration, evaporation from ground, from interception, deep leakage? How root depth-distribution is considered? How vegetation phenology is considered?

AR: We have added the descriptions of the stomatal conductance model in JSBACH, which is the most relevant part of the model to this work. We have no enough space in the manuscript to introduce details about soil hydrology and plant phenology of JSBACH model, however, please refer to the literatures cited in our manuscript. The five layer soil hydrology scheme has been introduced in Hagemann and Stacke (2015), and the plant phenology has been described in Böttcher et al. (2016).

Böttcher K., Markkanen, T., Thum, T., Aalto, T., Aurela, M., Reick, C. H., Kolari, P., Arslan, A. N., and Pulliainen. J.: Evaluating biosphere model estimates of the start of the vegetation active season in boreal forests by satellite observations, 8, 580, doi:10.3390/rs8070580, Remote Sens., 2016.

Hagemann, S. and Stacke, T.: Impact of the soil hydrology scheme on simulated soil moisture memory, Climate Dynamics, 44, 1731-1750, 2015.

Page 5. Line 146. Can the authors better characterize the spin-up? How long did you run? Which period did you use?

AR: Prior to the actual simulation, a 30-year spin-up run was conducted by cycling meteorological forcing that was used for the actual simulation to obtain equilibrium for the soil water and soil heat balances.

Page 5.Line 149. I would state that they were calculated from "observed data" rather than "model forcing". Are there any differences between the two?

AR: We agree with the reviewer. This paragraph seems no need to be there anymore as the data processing method has been updated in section 2.2. We have deleted this paragraph.

Page 5. Line 165-167. In my opinion, this classification of soil moisture conditions is very arbitrary, since there is no explicit link between the thresholds of SMI and plant physiologically meaningful variables such as "soil water potential" or better "leaf water potential". While overall, it is clear that with decreasing SMI drought stress should increase, there is no reason to support that drought stress should start at SMI of 0.1 or 0.4. I would suggest avoiding such classification and just having a continuous variable SMI.

AR: We have renamed the groups of SMI to described soil moisture conditions (very dry: $0 \leq SMI < 0.2$, moderate dry: $0.2 \leq SMI < 0.4$, mid-range: $0.4 \leq SMI < 0.6$, moderate wet: $0.6 \leq SMI < 0.8$, very wet: $0.8 \leq SMI < 1$) rather than drought conditions (severe drought: $0 \leq SMI < 0.2$, moderate drought: $0.2 \leq SMI < 0.4$, mid-range: $0.4 \leq SMI < 0.6$, moderate wet: $0.6 \leq SMI < 0.8$, very wet: $0.8 \leq SMI < 1$). In the revised manuscript, we used continuous color bar for SMI in the figures. However, we still need the SMI groups for fittings to describe the responses of GPP and ET to environmental variables under different soil moisture conditions.

Page 5. Line 171. I do not fully understand the rationale of using θsat in place of θfc. Even leaving a part the problematic concept of θfc (e.g. Assouline and Or 2014), the two values may be quite different and they are not interchangeable.

AR: This is a matter of introducing an offset. We were not meaning the two parameters are changeable. As θ_{FC} acts as a proxy for θ_{SAT} in the JSABCH model technically (Hagemann and Stacke, 2015), for consistency, the θ_{SAT} was used instead of θ_{FC} when calculating SMI based on the observed soil moisture data. By doing this, the SMI still indicates the soil moisture conditions and simulated SMI and observed SMI are comparable.

Page 5. Line 173-174. Also for Sodankylä, I 1do not understand why the authors did not use a soil water retention curve to link soil water contents to soil water potentials and therefore define some plant-meaningful threshold rather than arbitrary values.

AR: This is a very good suggestion and worth trying. However, we have decided to leave Sodankylä out and mainly focus on Hyytiälä site, as there was no severe drought happened in our study period at Sodankylä.

Page 6. Line 184. It is a measure of the inverse of the surface conductance.

AR: It is a measure of the surface conductance, but not inverse. Our original formulation was correct.

Page 6. Line 208-209. "deviated group" is awkward wording.

AR: It has been deleted.

Page 7. Line 235-236. As a follow up of my previous comment, SMI<0.2 does not necessarily imply a "drought" from the plant point of view and therefore the lack of deviation in GPP, ET, with respect to normal conditions should be expected as a consequence of the "lack of drought".

AR: Yes, we agree with the referee. Because there is no severe drought in the study period, we decided to not include the Sondankylä site anymore.

Page 8. Line 250-251. How many days are those for which we see such a deviation? Are they continuous in time? This is probably one of the most important information to place in the article, which needs to be emphasized.

AR: We agree with the referee. In the revised manuscript, we have emphasized and gave detailed information about the severe soil moisture drought in 2006 at Hyytiälä in section 3.1: "The SMI in the summer of 2006 showed a period with SMI evidently lower (< 0.2) than in other years during the 11-year study period. According to the in situ observed SMI, in the summer of 2006, there were 37 consecutive days (23 July to 28 August) with SMI lower than 0.2, and 17 consecutive days (1 August to 17 August) with SMI lower than 0.15. The lowest SMI from observation was 0.115 on 16 August 2006. The simulated SMI was generally smaller than the observed SMI in the summer of 2006, showing 42 consecutive days (17 July to 27 August) with SMI lower than 0.2, and 33 consecutive days (26 July to 27 August) with SMI lower than 0.15. The lowest SMI from simulation was 0.052 on 15 August 2006."

Page 8. Line 262-263. This is likely a consequence of the cross-correlation between high SMI and unfavorable meteorological conditions (e.g., cold, cloudy).

AR: Yes, we agree this could be the reason. We have added this in the discussion.

Page 9. Line 291-294. What is driving this proportionally larger decrease in GPP than ET? Looking from a leaf-level perspective this is hard to reconcile. What is keep sustaining ET if soil moisture is very low? How much is data uncertainty playing a role in such a response? Is it really just the change in VPD?

AR: The low soil moisture leads to stomatal closure, and therefore decreased GPP and Transpiration. The larger decrease in GPP than in ET at the ecosystem level was because that the increased atmospheric demand of water (VPD) stimulated Evaporation from soil. The reason has been discussed in the discussion part.

Page 11. Line 361-365. I agree that is important to highlight uncertainties of EC data, but how do you tackle this problem in the result presentation? There is not any confidence bound around the data, therefore we cannot really establish if some of data-driven result are very robust or not. At the very least, there should be a more quantitative discussion of the uncertainties.

AR: It is difficult to provide any confidence bound in the figures. Instead, we could add some general discussion related to the uncertainty of EC flux data which is typically 20-30% for annual carbon budget Baldocchi (2003) and Aubinet et al. (2012).

Aubinet, M., Vesala, T., and Papale, D.: Eddy covariance: a practical guide to measurement and data analysis, Springer Science & Business Media, Netherlands, 2012.

Baldocchi, D. D.: Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future. Global Change Biology, 9, 479–492, 2003.

Response to Anonymous Referee #5

General :

The general topic of the manuscript falls well within the scope of the journal. The manuscript presents an interesting study where the authors used eddy covariance (EC) method and a land surface model

(JSBACH) to assess the response of daily water use efficiency (WUE; both ecosystem and intrinsic) to drought in two boreal forest ecosystems in Finland. The manuscript is well-written but may benefit from careful editing. The manuscript contains some interesting results, and I recommend addressing some comments and suggestion raised below to make it clearer.

Specific comments:

Was nighttime data included in the analysis? Obviously, there is no assimilation during the night and the EC system may produce or the LSM may simulate negative ET values. This may not be easily detected if daily flux sums, as opposed to sub-daily fluxes, were used but the computed WUE values would be fundamentally flawed and have no meaning. Some of the simulated results still contain negative ET values but no corresponding WUE (IWUE) values are shown for such data in the graphs. I recommend that this issue be addressed in the manuscript.

AR: Agreed. The nighttime data were included in the analysis in the discussion manuscript. In the revised manuscript, according to reviewers' comments, only half-hourly data with shortwave radiation (Rs) larger than 100 W/m^2 were selected for the aim to select the effective time for plant photosynthesis. By doing this, data with negative GPP and ET were also excluded. The data selection process is described in section 2.2.

It is not clear how the authors treated data during rainy days. Rainy days may underestimate WUE as evaporation from the canopy surface would be high during such times. It is vital that the conclusions drawn in this study do not include such low WUE values.

AR: Agreed. In the revised data processing, rainy days and certain amount of dry days after the rainy days were excluded. The data selection process is described in section 2.2.

Lines 109–114: Could the authors provide information as what percentage of the data was observed and/or gap-filled for CO2 and H2O fluxes. The authors stated that only good quality gap-filled data were used in the analysis. It is not clear whether data were discarded at half-hourly or daily time scale; or what percentage of 'good quality gap-filled data' was regarded good enough to be used in the analysis.

AR: The original sentence was confusing and not totally correct. It has been deleted in the revised manuscript. Actually, the bad quality data was gap-filled, and the gap-filled data were used. The gap filling method for GPP and ET was introduced in section 2.2 in the manuscript. The percentage of gap-filled half-hourly CO_2 (for deriving GPP) is 35.8%, and the percentage of gap-filled half-hourly latent heat flux (for deriving ET) is 44.4%.

Lines 115–118 and lines 147–150: Were these (Ta, Rs and VPD) daily averages? If so please specify. Also in all the graphs where these weather variables are used. I would prefer total daily Rs to daily average Rs values though. Do observations and simulations use the same weather variables (I would assume so)? However, I see quite a number of 0 W m-2 Rs observations (at Hyytiälä which is south of Sodankylä!) but not so many in the simulations. These could be because the corresponding simulated y-axis variables were 0 as well. The question is how possible is it to have daily Rs of 0 W m-2 in the summer.

AR: Due to the new data processing for the revised manuscript, the Ta, Rs and VPD of the selected half hours in the selected days were averaged to represent the daytime mean Ta, Rs and VPD that effective

for plant functioning. The daytime mean Ta, Rs and VPD have been specified in the text and figure captions. For consistency with Ta and VPD, having just Rs per day does not make sense. We realized that the 0 W/m^2 Rs in the observational data is missing or bad quality data. However, those bad quality Rs has been gap-filled as the model forcing. In the revised manuscript, we selected the time periods with half-hourly Rs larger than 100 W/m^2 according to observational data for both observed flux and simulated flux. Thus the problem is not exist anymore in the revised manuscript.

Lines 119–122. Time Domain Reflectometry (not Reflection). Also theta probe is not a technique, it is a sensor. It would be better if you mention the names (models) of the sensors and manufacturers, and readers could find out the techniques should they be interested.

AR: The soil water content at Hyytiälä was measured at 1-h intervals by the TDR-method (Tektronix 1502 C cable radar, Tektronix Inc., Redmond, USA) connected to a data logger (Campbell 21X, Campbell Scientific Ltd, Leics., UK) via multiplexers (SDMX50, Campbell Scientific Ltd, Leics., UK). We are not using Sodankylä site for our study in the revised manuscript.

As the soil water content forms the core of the simulation results, it would be helpful if the authors could provide more information on sensor types, how they were installed (vertically, horizontally or make use of access tube), if they were static or portable, measurement (time) interval, replications at a site, etc. Besides, was the soil water content for each sensor and depth calibrated against standard gravimetric measurements?

AR: At Hyytiälä site, instrumentation for soil moisture was installed horizontally in the vertical face of five soil pits for each soil horizon (humus at 3 cm depth, the eluvial horizon at 8 cm depth, the illuvial horizon at 19 cm depth and parent material at 55 cm depth) 2 years before measurements were taken. The instruments were installed in the middle of each soil horizon, in the undisturbed soil at 20±30 cm distance from the face of the pit. Samples for measuring soil physical and chemical properties were collected from the walls of the pits during the excavation. The pits were filled with the original soil keeping the soil layers in the original order of excavation. We study the soil water content in mineral soil layers with the humus layer excluded. In the soil moisture data, the depth of mineral soil layers starts from 0 at the mineral soil surface.

Why was the 0 to -5-cm soil water content at Hyytiälä disregarded in the observed vs simulated comparisons?

AR: Because the soil moisture at the top mineral soil (i.e., layer-1) is too sensitive to climate varibility, which is not representative to show the soil moisture dynamics in the root zone. This is explained in the text in the revised manuscript.

Lines 161–167: Again, it is not clear why observed and simulated SMI for layer 1 were not used, at least for Hyytiälä. And, how could the observed and simulated SMI be compared when the depth of the third layer is different for the two (at Hyytiälä)?

AR: The 1st layer of the measured and the simulated soil moisture were not adopted because there is too much variability of the surface soil moisture in response to climate variability. This has been explained in the text in the revised manuscript. We selected the second and the third observed layers to cover the root depth. This has been correlated with simulations to select the best correspondence. The difference remains to some degree. In the revised manuscript section 3.1, the simulated SMI that calculated with simulated soil moisture and soil parameters in JSBACH has been compared with the observed SMI that

based on observed soil moisture and measured soil parameters. The simulated SMI agreed well with in situ observed SMI over the 11-year study period, with a correlation coefficient (0.625) and a root-mean-square error (RMSE) of 0.225. Moreover, a very good time correlation (0.965) between simulated and observed SMIs were found for year 2006, despite the simulated SMI is systematically lower than the observed SMI (RMSE = 0.12).

165–179: Lack of measured soil parameters was the reason behind adopting different soil moisture classification units for the two locations. If there was continuous long-term soil water content data for so many years, it would not have been so difficult to derive these soil parameters (at Sodankylä). Saturated and field capacity soil water content may be estimated in spring following snowmelt, and wilting point from extended dry periods later in summer.

AR: We agree with the reviewer's opinion. It would be good to estimate the soil parameters from long-time series data. However, the whole data series which is 8-year (2001-2008) data for Sodankylä site were used. Nevertheless, since there was no severe drought in the 8-year study period at Sodankylä, we decided to not include this site in the revised manuscript but mainly focus on the severe drought and its impacts at Hyytiälä site.

Assuming the soils are similar at the two sites, it seems unlikely that the very wet conditions at Sodankylä would only have a soil water content of 13 to 16 .

AR: The soil type is podzol at both sites. However, the mineral soil in Hyytiälä (the composition of mineral soil in 0-22 cm: clay 6%, silt 29%, sand 38%, stones 27%) is much finer than Sodankylä (the composition of mineral soil in 0-20 cm: clay 0.4%, silt 5.1%, sand 90.8%, stones 3.8%). This explains why the volumetric soil water content is much lower in Sodankylä.

Lines 194–199: Could the authors provide R2 and P values for the graphs? What was the improvement in R2 and P values due to adopting exponential rather than linear relationship between GPP and ET or T?

AR: The reason for adopting exponential rather than linear relationship is that more physiological relationships than just linear were used when existing. The R2 and P values for the relationships between GPP, ET or T and environmental variables (Rs, Ta and VPD) are provided in the table in the supplementary of revised manuscript.

Lines 205–208: In general, there are more points in zone (b) than in zone (a); and zone (b) includes a larger range of the environmental variables. Both zones share more common than different environmental variables. I wonder if the environmental variables could be used at all to tease out differences in drivers between the two zones (apart from SMI).

AR: This is exactly what we wanted to present that the zone (a) and zone (b) share more common environmental variables but have different soil moisture conditions. Moreover, in the revised manuscript, due to the new process of data, a group of data under low soil moisture content (encircled with a dashed line in Fig. 2(a)) showing GPP values lower than other days. The ET values of this group are also located in the lower end, but just partly lower than ET values on other days. It is found that the days in this group are all with very low soil moisture condition (SMI < 0.15). The old group (a) is not exist anymore with the exclusion of rainy days.

Line 222: There are negative simulated ET values (Figs. S1, S2, S5, etc.). Could the authors explain

how they treated such data when determining WUE?

AR: Those negative simulated ET values were dampened by daily averaging due to nighttime condensation. Through the reprocessed of the data for the analysis, only daytime data without precipitation influence were selected. The data selection process is described in section 2.2. In the revised manuscript, only half-hourly data with shortwave radiation (Rs) larger than 100 W/m^2 were selected for the aim to select the effective time for plant photosynthesis. The rainy days and certain amount of dry days after the rainy days were also excluded. By doing this, data with negative GPP and ET were excluded. Therefore, there is no problem of the influence from negative ET on WUE anymore.

Lines 294–297: It would be better if the y-axis of Figs. 4 and S5 were IWUE rather than GPP×VPD. As it is, it is difficult to tell whether IWUE increases or decreases with ET.

AR: The increase or decrease of IWUE can be seen from the ratio of GPP×VPD to ET, as the definition of IWUE.

Be consistent in using either soil water content or soil moisture throughout.

AR: We will use soil moisture throughout the text.

Line 18 to 20: This is not clear at all. Rewrite please.

AR: We have revised this sentence.

Line 58: Change ". . . the ratio of GPP and ET." to ". . . the ratio of GPP to ET."

AR: Agreed. It has been changed.

Lines 80 to 83: Does not read well. Consider rewording–for example to ". . . the various land ecosystem model simulations highlight the current uncertainty with regard to plant physiology (water use) in response to drought."?

AR: We have revised the sentence as: "The various land ecosystem model simulations highlight the current uncertainty about plant physiology (water use) in response to drought in models (Huang et al., 2015; Jung et al., 2007)."

Lines 91 and 92: Consider removing this sentence and start with the actual experimental sites.

AR: Agreed. This part has been rewritten for the Hyytiälä site.

Line 93: 'annual temperature' should read 'annual air temperature'. Also in Table 1 (Lines 600–605).

AR: Agreed. It has been changed.

Line 116: Humidity is ambiguous term to use. Be specific which measure of atmospheric humidity was used.

AR: Agreed. It has been changed.

Line 153: Delete the phrase 'to be able'

AR: We have deleted the "to be able".

Line 157: ". . .] and θWILT is the . . ."

AR: This has been changed according to the comment.

Line 170: ". . . (i.e., soil water content . . ."

AR: This has been changed according to the comment.

Line 170: ". . . and θWILT= . . .)"

AR: This has been changed according to the comment.

Line 171–172: Confusing statement. This changes the definition of SMI and probably the boundaries of SMI set-up above. And, if θFC acts as a proxy for θSAT, then should not θFC be used instead of θSAT?

AR: Because θ_{FC} plays the role as θ_{SAT} in the JSABCH model technically (Hagemann and Stacke, 2015), for consistency, the θ_{SAT} was used instead of θ_{FC} when calculating SMI based on the observed soil moisture data. By doing this, the SMI still indicates the soil moisture conditions, and simulated SMI and observed SMI are comparable. Using θ_{FC} or θ_{SAT} is a matter of introducing an offset.

Line 192 onwards: ET/T is ambiguous. Use ET or T instead.

AR: This has been changed according to the reviewer's suggestion.

Line 248: Replace 'slop' with 'slope' in Tables S1 and S2.

AR: Indeed. It has been changed.

Line 300: Simulated EWUE is not presented in Fig. S5.

AR: The simulated EWUE is now shown in the supplementary figure.

Lines 304–305: This sentence is not a result. Move it to the Discussion Section.

AR: We agree with the reviewer. However, this part about Sodankylä results has been deleted in the revised manuscript.

Lines 313, 320 and 337: Consider changing the word 'disturbance'. Some suggestions:
Line 313: 'Moreover, GPP and ET were decoupled and EWUE decreased . . .', Line 320: '. . . there was no deviation in GPP, . . .', and Line 337: 'The simulated daily ET data contained frequent . . .'.

AR: We have revised the sentence in Line 313. The other two sentences are not exit in the revised manuscript due to the exclusion of Sodankylä site in the revision.

Line 341: '. . . limitations on GPP and ET or T relationships under . . .'.

AR: We do not agree to add "relationships" in the sentence as we referred to the impacts of drought on GPP and ET.

Line 344: '. . . when soil moisture was under . . .'.

AR: We agree with the reviewer about this grammar mistake. The sentence has been modified.

Line 370: Delete 'as a whole'

AR: Yes, this has been deleted.

Response of water use efficiency to summer drought in a boreal Scots pine forest in Finland

Yao Gao[1], Tiina Markkanen[1], Mika Aurela[1], Ivan Mammarella[2], Tea Thum[1], Aki Tsuruta[1], Huiyi Yang[3], Tuula Aalto[1]

[1]Finnish Meteorological Institute, Helsinki, P.O. Box 503, 00101, Finland
[2]Department of Physics, University of Helsinki, Helsinki, P.O. Box 48, 00014, Finland
[3]Institute for Climate and Atmospheric Science, School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK

Correspondence to: Yao Gao (yao.gao@fmi.fi)

Abstract. The influence of drought on plant functioning has received considerable attention in recent years, although our understanding of the response of carbon and water coupling to drought in terrestrial ecosystems still needs to be improved. A severe soil moisture drought occurred in southern Finland in the late summer of 2006. In this study, we investigated the response of water use efficiency to summer drought in a boreal scots pine forest (*Pinus sylvestris*) at the daily time scale mainly using eddy covariance flux data from the Hyytiälä (southern Finland) flux site. In addition, simulation results from the JSBACH land surface model were evaluated against the observed results. Based on observed data, the ecosystem level water use efficiency (EWUE, the ratio of gross primary production (GPP) to evapotranspiration (ET)) showed a decrease during the severe soil moisture drought, while the inherent water use efficiency (IWUE, a quantity defined as EWUE multiplied with mean daytime vapour pressure deficit (VPD)) increased and the underlying water use efficiency (uWUE, a metric derived based on IWUE and a simple stomatal model, which is the ratio of GPP multiplied with a square root of VPD to ET) was insensitive to the drought. The decrease in EWUE was due to the stronger decline in GPP than in ET. The increase in IWUE means that the surface conductance at the ecosystem level was decreased and the intrinsic water use efficiency at the ecosystem level was enhanced during the severe soil moisture drought. The insensitivity of uWUE to this relatively short-term drought event indicates that uWUE is probably more suitable for studying the effects of long-term environmental changes on plant functioning. Overall, IWUE is most sensitive among the three metrics to stomatal closure during the drought event. IWUE is a more appropriate metric than EWUE and uWUE for capturing the impact of summer drought on plant functioning at the daily time scale. The JSBACH simulation showed declines of both GPP and ET under the severe soil moisture drought, but to a smaller extent compared to the observed GPP and ET. The model deficiencies exist mainly due to the lack of the limiting effect of increased VPD on stomatal conductance during the low soil moisture condition. Simulated GPP and ET led to a smaller decrease of EWUE but a larger increase in IWUE because of the severe soil moisture drought in comparison to observations. As in the observations, the simulated uWUE showed no changes in the drought event because it is more independent of VPD. Our study provides deeper understanding of coupling of carbon and water cycles in the major boreal ecosystem scots pine forests. These findings highlight the importance of choosing a suitable plant functioning indicator when investigating the effects of drought, and suggest possible improvements to land surface models, which play an important role in the prediction of biosphere-atmosphere feedbacks in the climate system.

Keywords: drought response, boreal forests, eddy covariance, water use efficiency, soil moisture drought, land surface model

1. Introduction

Terrestrial plants assimilate carbon dioxide (CO_2) through photosynthesis accompanied by a loss of water (H_2O) in transpiration. Both processes are strongly regulated by plant physiology (e.g., stomatal conductance; g_s) and local environmental conditions. Plants protect themselves from excessive water losses (diffusion out of the leaf) under water-limited environments through a reduction of stomatal conductance, which in turn leads to less carbon uptake (diffusion of CO_2 into the leaf) and possibly subsequent physiological stress (McDowell et al., 2008; Will et al., 2013).

Soil water deficit can induce a reduction of transpiration (Bréda et al., 1993; Clenciala et al., 1998; Granier et al., 2007; Irvine et al., 1998), and it has been recognized as the main environmental factor limiting plant photosynthesis at global scale (Nemani et al., 2003). Even though the occurrence of drought is low in northern Europe, the summer of 2006 in Finland has been found to be extremely dry and 24.4 % of the 603 forest health observation sites over entire Finland showed drought damage symptoms in visual examination, in comparison to 2–4 % damaged sites in a normal year (Muukkonen et al. 2015). The spatial distribution of the drought damages has been found to be closely related to the plant available soil moisture (Gao et al., 2016).

Water Use Efficiency (WUE) is a critical metric that quantifies the trade-off between photosynthetic carbon assimilation and transpiration at the leaf level (Farquhar et al., 1982). WUE can be used to study ecosystem functioning which is closely related to the global cycles of water, energy and carbon (Keenan et al., 2013). With the use of the eddy covariance technique (EC) and associated data processing, i.e., the derivation of gross primary production (GPP) and evapotranspiration (ET) from measurements of CO_2 flux and latent heat flux, WUE can be calculated at the ecosystem scale as the ecosystem level water use efficiency (EWUE), which is the ratio of GPP to ET. EWUE is broadly adopted as a surrogate for the leaf level WUE in many studies, because more data are available at the ecosystem level than at the leaf level (Arneth et al., 2006; Law et al., 2002; Lloyd et al., 2002).

Reichstein et al. (2007) observed a small decrease in EWUE in the majority of the 11 studied EC sites during the 2003 summer heatwave in Europe. However, their findings are at odds with many models that describe the environmental controls on stomatal conductance, with increased EWUE predicted during drought periods (Schulze et al., 2005). Many of those models are based on the optimality theory by Cowan and Farquhar (1977) who proposed that plants are able to regulate stomatal conductance in order to maximize WUE. Granier et al. (2008) reported that EWUE increased linearly with soil water deficit duration and intensity at a young beech forest site in north-eastern France. Moreover, EWUE also increased substantially at two forest sites, but not at grassland sites, during the 2011 spring drought in Switzerland (Wolf et al., 2013). However, no differences in EWUE were shown between abundant- and low-rainfall years at a boreal Scots pine forest site in south-eastern Finland, even though GPP was reduced during low-rainfall years with long-lasting drought periods (Ge et al., 2014). Therefore, the impact of drought on EWUE remains unclear. Beer et al. (2009) concluded that the impact of vapour pressure deficit (VPD) on canopy conductance disturbs responses of both GPP and ET to changing environmental conditions. Thus, to investigate the intrinsic link between carbon and water fluxes through stomatal conductance at the ecosystem level, Beer et al. (2009) have proposed the ecosystem level inherent water use efficiency (IWUE), which is a quantity defined as EWUE multiplied with mean daytime VPD. IWUE has been found to increase during short-term moderate drought (Beer et al., 2009). Moreover, based on IWUE and a simple stomatal model of Lloyd and Farquhar (1994), the underlying water use efficiency (uWUE) has been introduced to exclude the nonlinear dependence of IWUE on VPD and the linear relationship between GPP

multiplied with a square root of VPD and ET has been found at the half-hourly time scale by Zhou et al. (2014). Later on, the appropriateness of uWUE at the daily time scale has been demonstrated (Zhou et al., 2015).

Given the need to understand and project feedbacks between climate change and plant physiological responses, it is crucial to be able to realistically model the plant controls of stomatal conductance, and photosynthesis and transpiration responses under water stress (Berry et al., 2010; Knauer et al., 2015; Zhou et al., 2013). The various land ecosystem model simulations highlight the current uncertainty about plant physiology (water use) in response to drought in models (Huang et al., 2015; Jung et al., 2007).

The objectives of this study are (1) to understand the environmental controls on GPP and ET fluxes during a summer drought in boreal Scots pine (*Pinus sylvestris*) forests at a EC flux site in southern Finland, (2) to investigate the drought impact on WUE metrics, including EWUE, IWUE and uWUE, (3) to evaluate how adequately plant responses to changes in environmental variables are captured by the JSBACH land surface model (LSM).

2. Data and methods

2.1 Study sites

The Hyytiälä flux site is located in southern Finland (61°51′N, 24°17′E, 180 m a.s.l.) at the SMEAR-II (Station for Measuring Ecosystem-Atmosphere Relations) field measurement station (Hari and Kulmala, 2005). The site is dominated by 55-year-old boreal Scots pine (*Pinus sylvestris*), which is homogeneous about 200 m in all directions from the site and extends to the north for about 1 km (Mammarella et al, 2007). The canopy height of trees is about 13-16 m and the mean all-sided leaf area index (LAI) is 6 m^2/m^2. The soil at the site is Haplic podzol on glacial till (FAO-UNESCO, 1990). The 30-year (1961-1990) averaged annual mean air temperature is + 2.9 °C and precipitation is 709 mm at the site (Vesala et al., 2005). Those details about the site are listed in Table 1. The ground vegetation consists mainly of blueberry (*Vaccinium myrtillus*), lingonberry (*Vaccinium vitis-idaea*), feather moss (*Pleurozium schreberi*) and other bryophytes (Kolari et al., 2009). We analysed the summer (June-August) from an 11-year period (1999-2009) according to data availability.

2.2 Flux measurement and data processing

Ecosystem carbon and water fluxes at the site were measured with the micrometeorological EC method. Turbulent fluxes were calculated as half-hourly averages following standard methodology (Aubinet et al., 2012) with EddyUH software (Mammarella et al., 2016 et al., 2015).). The vertical CO_2 flux was obtained as the covariance of high-frequency (10 Hz) observations of vertical wind speed and the CO_2 concentration (Baldocchi, 2003). The CO_2 flux was corrected for storage change to obtain net ecosystem CO_2 exchange (NEE), which was then partitioned into total ecosystem respiration (TER) and GPP according to Kolari et al. (2009). Data quality of 30 min values of NEE and latent heat flux (LE) was ensured excluding records with low turbulent mixing (friction velocity below 0.25 m/s) as described in Markkanen et al. (2001), Mammarella et al (2007) and Ilvesniemi et al. (2010). TER was modelled using an exponential equation with temperature at a depth of 2 cm in the soil organic layer as the explanatory factor. The value of GPP was then directly derived as residual from the measured NEE. When NEE was missing, GPP was gap-filled according to Kolari et al. (2009). LE was gap-filled using a linear regression against net radiation in a moving window of 5 days, and then ET was inferred from LE.

In addition to the EC measurements, a set of supporting meteorological variables were adopted as half-hourly averages;
115 incoming shortwave radiation (R_s) and longwave radiation, air temperature (T_a), atmospheric humidity, precipitation were used as meteorological forcing for the site level simulation. The soil moisture was monitored at 1-hour intervals by the Time Domain Reflectometry (TDR) method (Tektronix 1502 C cable radar, Tektronix Inc., Redmond, USA). Three layers of mineral soil (0 to −5, −5 to −23 and −23 to −60 cm) were measured, as well as the organic layer on the top (-4 to 0 cm). In this study, soil moisture at the two lower levels (-5 to -23 and -23 to -60 cm) at Hyytiälä was averaged over a day to represent
120 daily soil moisture dynamics in the root zone at the site. The reason to exclude layer 1 soil moisture is that it is too sensitive to climate variability.

The half-hourly data of GPP and ET, as well as meteorological variables were averaged over the selected time periods in a day. Prior to averaging, rainy days and a number of dry days after the rainy days were firstly excluded from the data. The
125 number of excluded dry days was determined by the ratio of daily precipitation to potential evapotranspiration (PET). When precipitation was smaller than PET, no dry day after rainy day was excluded. When precipitation was equal or larger than twice of PET, two dry days following the rainy day were excluded. Additionally, when precipitation was larger than PET but with the ratio less than two, one dry day after the rainy day was excluded. PET was calculated using the Penman-Monteith equation and the 'Evapotranspiration' Package in R software was used (Guo et al., 2016). Second, in order to capture the daily
130 time periods of effective photosynthesis, only half-hourly data with R_s larger than 100 W/m^2 were selected. Finally, the half-hourly data of R_s, VPD, and T_a were also averaged over the selected time periods to get their daytime mean values respective to the GPP and ET data. The same data processing method was used for the simulation results.

2.3 JSBACH land surface model

JSBACH (Raddatz et al., 2007; Reick et al., 2013) is the LSM of the Max Planck Institute for Meteorology Earth System
135 Model (MPI–ESM) (Roeckner et al., 1996; Stevens et al., 2013). The land physics of JSBACH mainly follow those of the global atmosphere circulation model ECHAM5 (Roeckner et al., 2003), and the biogeochemical components are mostly taken from the biosphere model BETHY (Knorr, 2000). In JSBACH, land vegetation cover is described as plant functional types (PFTs) and a set of properties (e.g., maximum LAI, albedo) is attributed to each PFT with respect to the processes that are accounted for by JSBACH. The phenology model (Logistic Growth Phenology; LoGro-P) of JSBACH simulates the LAI
140 dynamics to compute photosynthetic production (Böttcher et al., 2016). The models of Farquhar et al. (1980) and Collatz et al. (1992) are used for photosynthesis of C3 and C4 plants, respectively. A five layer soil hydrology scheme was implemented in JSBACH by Hagemann and Stacke (2015). Gao et al. (2016) has demonstrated that JSBACH with its five-layer soil hydrology scheme is able to capture the soil moisture dynamics at sites and in the regional scale of Finland.

145 2.3.1 **The stomatal conductance model in JSBACH**

The current version of the stomatal conductance model in JSBACH considers the limitation from soil water availability on stomatal conductance (g_s), which further impacts on carbon assimilation and transpiration.

150 Firstly, the net assimilation rate (A_n [mol m^{-2} s^{-1}]) and g_s [mol m^{-2} s^{-1}] are calculated for without water limitation as the unstressed net assimilation rate ($A_{n,pot}$ [mol m^{-2} s^{-1}]) and the unstressed stomatal conductance ($g_{s,pot}$ [mol m^{-2} s^{-1}]). The $A_{n,pot}$ is

calculated using the photosynthesis model in JSBACH, for which the intercellular CO_2 concentration under unstressed condition ($C_{i,pot}$ [mol mol^{-1}]) is needed. The $C_{i,pot}$ is prescribed using the atmospheric CO_2 concentration (C_a [mol mol^{-1}]), where $C_{i,pot} = 0.87C_a$ for C3 plants and $C_{i,pot} = 0.67C_a$ for C4 plants (Knorr, 2000). After the $A_{n,pot}$ is determined, the $g_{s,pot}$ is

155   derived using the following equation:

$$g_{s,pot} = \frac{1.6A_{n,pot}}{C_a - C_{i,pot}} \quad\quad\quad\quad\quad\quad (1)$$

Then, an empirical water stress factor, which is a function of volumetric soil moisture, is used to derive g_s [mol m^{-2} s^{-1}] from $g_{s,pot}$ as follows:

$$g_s = \beta g_{s,pot} \quad\quad\quad\quad\quad\quad (2)$$

160   where

$$\beta = \begin{cases} 1 & \theta \geq \theta_{crit} \\ \frac{\theta - \theta_{wilt}}{\theta_{crit} - \theta_{wilt}} & \theta_{wilt} < \theta < \theta_{crit} \\ 0 & \theta \leq \theta_{wilt} \end{cases} \quad\quad\quad\quad (3)$$

herein, θ [m^3 m^{-3}] is the volumetric soil moisture, θ_{crit} [m^3 m^{-3}] is the critical point and θ_{wilt} [m^3 m^{-3}] is the permanent wilting point.

Finally, the intercellular CO_2 concentration (C_i) and A_n are resolved using g_s. The canopy conductance (G_c [mol m^{-2} s^{-1}]) and

165   canopy-scale A_n are integrated over the leaf area. Unlike the BETHY approach (Knorr, 2000), the control of g_s in JSABCH does not include the influence of atmospheric humidity.

2.4 Site level simulation by JSBACH

170   For the site simulation, JSBACH was forced with the half-hourly local meteorological observations. Based on the site-specific information, PFT was assigned as evergreen needle leaf forest and the soil type was set as loamy sand in JSBACH. The maximum LAI was set according to observed values. Also, the maximum carboxylation rate (Jmax) and maximum electron transport rate (Vmax) at 25 °C were adjusted, for the simulated GPP to match the magnitude of the observed GPP. The Vmax was set to be 37.5, and the Jmax was 71.3. The soil depth and root depth at the site were derived from maps for the regional

175   JSBACH simulation presented in Gao et al. (2016) (see also Hagemann and Stacke, 2015). Those parameter settings in the JSBACH site level simulation for the site are listed in Table 1. Prior to the actual simulations, a 30-year spin-up run was conducted by cycling meteorological forcing that was used for the actual simulation to obtain equilibrium for soil water and soil heat balances.

2.5 Soil Moisture Index (SMI)

180   In this study, the soil moisture dynamics are represented by SMI (also referred to as Relative Extractable Water – REW), which has been demonstrated to represent summer drought in boreal forests in Finland (Gao et al., 2016). The SMI describes the ratio of plant available soil moisture to the maximum volume of water available to plants in the soil (Betts, 2004; Seneviratne et al., 2010):

SMI = $(\theta - \theta_{WILT})/(\theta_{FC} - \theta_{WILT})$, $\quad\quad\quad\quad\quad\quad$ (4)

185 where θ is the volumetric soil moisture [$m^3\,H_2O\,m^{-3}$], θ_{FC} is the field capacity [$m^3\,H_2O\,m^{-3}$] and θ_{WILT} is the permanent wilting point [$m^3\,H_2O\,m^{-3}$]. When θ exceeds θ_{FC}, soil water cannot be retained against gravitational drainage, while below θ_{WILT}, the soil water is strongly held by the soil matrix and cannot be extracted by plants (Hillel, 1998). In this study, soil moisture conditions were classified to five groups according to SMI values with an interval of 0.2: very dry: $0 \le SMI < 0.2$, moderate dry: $0.2 \le SMI < 0.4$, mid-range: $0.4 \le SMI < 0.6$, moderate wet: $0.6 \le SMI < 0.8$, very wet: $0.8 \le SMI < 1$.

190

From simulations, we used the average of the second layer (layer-2; 6.5–31.9cm) and the third layer (layer-3; 31.9–123.2 cm) soil moisture together with model soil parameters to determine SMI for Hyytiälä to correspond with the two lower levels of the observed soil moisture. For the SMI derived from the observed soil moisture at Hyytiälä, the measured soil parameters were adopted (i.e., volumetric soil moisture at saturation (θ_{SAT}) = 0.50 $m^3\,H_2O\,m^{-3}$, θ_{FC} = 0.30 $m^3\,H_2O\,m^{-3}$ and θ_{WILT} = 0.08

195 $m^3\,H_2O\,m^{-3}$). As θ_{FC} acts as a proxy for θ_{SAT} in JSBACH model (Hagemann and Stacke, 2015), θ_{SAT} was used instead of θ_{FC} for consistency when calculating SMI based on the observed soil moisture data.

2.6 Ecosystem Water Use Efficiency (EWUE), Inherent Water Use Efficiency (IWUE) and Underlying Water Use Efficiency (uWUE)

200
At the ecosystem level, water use efficiency is calculated as,

EWUE = GPP/ET, (5)

IWUE at the ecosystem level is defined as EWUE multiplied by daytime mean VPD, and ET/VPD is a hydrological measure of the surface conductance at the ecosystem level (Beer et al., 2009),

205 IWUE = GPP×VPD/ET, (6)

uWUE at the ecosystem is derived based on IWUE and a simple stomatal model of Lloyd and Farquhar (1994). The formulation of uWUE is,

uWUE = GPP×$VPD^{0.5}$/ET (7)

210 From EC data EWUE and IWUE can only be calculated with ET, which, in addition to transpiration, contains evaporation of water intercepted by surfaces and soil evaporation. However, process-based ecosystem models do resolve evaporation and transpiration which together compose ET. Therefore, transpiration-based EWUE, IWUE and uWUE can also be calculated using simulated transpiration instead of ET in those equations.

3. Results

215 **3.1 Soil moisture drought at Hyytiälä in 2006**

In the summer of 2006, a period with evidently lower SMI values (< 0.2) than in any other year during the 11-year time series was shown (Fig. 1 (a)). According to the in situ observation, in the summer of 2006, there were 37 consecutive days (23 July to 28 August) with SMI lower than 0.2, and 17 consecutive days (1 August to 17 August) with SMI lower than 0.15. The observed SMI reached its minimum of 0.115 on 16 August 2006. The simulated SMI was generally smaller than the observed

220 SMI in the summer of 2006, showing 42 consecutive days (17 July to 27 August) with SMI lower than 0.2, and 33 consecutive

days (26 July to 27 August) with SMI lower than 0.15. The lowest SMI from simulation was 0.052 on August 15th. The simulated SMI agreed well with in situ observed SMI over the 11-year study period, with a correlation coefficient (0.625) and a root-mean-square error (RMSE) of 0.225. However, the simulated SMI showed larger amplitude and a faster response to changes in climate conditions in comparison to the observed SMI. Nevertheless, a very good time correlation (0.965) between
225 simulated and observed SMIs were found for year 2006 (Fig. 1 (b)), despite the simulated SMI was systematically lower than the observed SMI (RMSE = 0.12).

Concurrently with the low soil moisture, a high T_a anomaly was presented in August 2006 (Fig. 1 (c)). In all the days in August 2006, the daily mean in situ T_a was higher than the 11-year averaged daily mean T_a. The monthly averaged daily mean T_a in August 2006 (18.1 °C) was 3.1 °C higher than the 11-year averaged daily mean T_a in August (15.0 °C). Also, the daily
230 mean VPD in August 2006 is higher than the 11-year averaged daily mean VPD in August in general (not shown), except on the days with precipitation. Especially, the daily mean VPD in the first-half of August (31 July to 16 August) was substantially higher (0.485 kPa) than the 11-year averaged daily mean VPD over this period. The biggest difference of 1.054 kPa took place on August 5th, the day with highest T_a in August 2006. Also, the daily mean R_s in the summer of 2006 was overall higher than the 11-year averaged daily mean R_s, with the monthly mean values by 15.4%, 31.2% and 21.4 % higher in June, July
235 and August respectively.

The precipitation events have strong impact on the temporal pattern of SMI. The cumulative in situ precipitation of 34.3 mm in July 2006 was the lowest during the 11-year study period with the July average of 91.0 mm. In contrast, the highest total precipitation in July was in 2007, reaching 145.5 mm. The cumulative precipitation of 47.7 mm in August 2006 was not as low as in July when compared to the 11-year average of 70.6 mm. However, the lack of precipitation since the end of July led
240 to the continuous drop of SMI by mid August 2006, followed by a small increase in soil moisture after a light precipitation event. The soil moisture increased to above 0.2 in the end of August with a heavy precipitation event exceeding 25.0 mm in one day. Moreover, the precipitation in June 2006 was also less than the average (45.2 vs. 70.0 mm) and temporally unevenly distributed, with only a small amount in the beginning of June and a large amount in the end of June. Therefore, there was a continuous decrease of soil moisture from the beginning of June and an abrupt increase in SMI of more than 0.1 in the end of
245 June.

3.2 The relationship of GPP to ET categorized by environmental variables

In general, the daytime averaged GPP and ET from observations at Hyytiälä showed a non-linear relationship (Fig. 2 (a)). When categorized according to environmental variables, there is a group of data under the very dry soil moisture condition (encircled with a dashed line in Fig. 2 (a)) showing GPP values lower than other days. The ET values of this group are also
250 located in the lower end, but just partly lower than ET values on other days. It is found that the days in this group are with SMI smaller than 0.15. Moreover, there are only two days with SMI values smaller than 0.15 that are not included in the encircled group due to their slightly higher GPP values. Most of the days in the group have high daytime mean T_a (18 to 24 °C), sufficient daytime mean R_s (mostly above 300 W/m^2), and relatively high daytime mean VPD (above 1 kPa).

255 The relationship between the daytime averaged GPP and ET from the JSBACH simulation is more constrained to a non-linear relationship in comparison to the observation (Fig. 2 (b)). The decline of both GPP and ET during low SMI was captured by the model. However, under the very low soil moisture condition (SMI < 0.15) during the summer drought in 2006, the model

simulated much less stress on the reduction of GPP, while the ET decreased to be lower than the observation in few days. The non-linear relationship between simulated daytime averaged GPP and transpiration (Fig. S1 in supplementary) is similar to the relationship between simulated daytime averaged GPP and ET, which demonstrates that transpiration composes a large fraction of ET at daytime at the site, especially under soil water stress. Except the drought events, GPP and ET both increased with increasing R_s and VPD in the simulation, which was more evident than in the observational data.

3.3 Response of GPP and ET to environmental variables categorized by SMI

The dependence of GPP and ET on environmental variables was further investigated for different SMI ranges (Fig. 3). The exclusion of the nighttime and the days affected by rain (see details in section 2.2) removed also the small values of GPP and ET. Thus, linear regressions were fitted between GPP (ET) and environment variables for each soil moisture group to emphasize the deviating differences of dependence of GPP (ET) on environmental variables under different soil moisture conditions. The regression parameters, coefficients of determination and statistical significance are summarized in Table S1 in the Supplementary Material.

The very dry soil ($0 \leq SMI < 0.2$) led to a response of observed daytime mean GPP and ET to daytime mean R_s, T_a and VPD that deviated considerably from the responses of the daily mean SMI values greater than 0.2 (Fig.3 (a)). Under the very dry soil moisture condition, GPP decreased with the declining SMI with a high correlation of 0.79, whereas the other SMI groups showed more scattered relationship between GPP and SMI. Different from the other SMI groups, GPP was the most negatively correlated with T_a and VPD under the very dry soil moisture condition. Moreover, the group with SMI values less than 0.2 displayed lower GPP values (on average 97.6 μg C m^{-2}s^{-1}) than the other groups (on average 151 μg C m^{-2}s^{-1}). The response patterns of the observed ET to environmental variables were similar to those of GPP. As with GPP, the group under the very dry soil moisture condition deviated strongly from the other SMI groups. However, the decrease in ET under severe soil moisture drought was not as pronounced as in GPP.

For the simulated GPP and ET too, the group under the very dry soil moisture condition deviated from the other SMI groups, but not to the same extent as that in the observed GPP and ET. Under other soil moisture conditions (SMI >0.2), the simulated GPP had stronger positive linear relationships with daytime mean R_s, T_a and VPD than the observed GPP. Compared to the observed ET, some differences existed in the response of the simulated ET to environmental variables. First, the dependence of simulated ET on R_s tended to be more linear than the observed ET and R_s relationship. Second, unlike observed ET, the simulated ET increased concomitantly with VPD at high VPD. Nevertheless, simulated ET of the group under severe soil moisture drought deviated strongly from the other SMI groups, but to a less extent than observed ET.

3.4 Soil moisture drought impacts on EWUE, IWUE and uWUE

From the observation, the decrease in GPP was much stronger than the decrease in ET during the soil moisture drought, which resulted in largely decreased EWUE that reached the recorded minimum during the severe soil moisture drought (Fig. 2 and Fig. S2 in Supplementary Material). In contrast to EWUE, IWUE increased from 3.25 (the mean value for the days with SMI smaller than 0.2) to 3.93 (the mean value for the days with SMI equal or larger than 0.2), and uWUE did not change under the severe soil moisture drought at Hyytiälä (Fig. 4 (a)). The simulated EWUE decreased less and the simulated IWUE increased more (from 3.62 to 5.17) than the observation, which is mainly because of a smaller decrease of the simulated GPP

295 than its observed counterpart during the soil moisture drought (Fig. 4 (b)). The simulated uWUE remained insensitive to the severe soil moisture drought. In addition, the transpiration based EWUE, IWUE and uWUE (Fig. S3 in Supplementary Material) showed similar results to those three metrics calculated with ET.

4. Discussion

300 **4.1 Drought impacts on GPP and ET**

Both GPP and ET were suppressed when there was the severe soil moisture drought in the summer of 2006 at Hyytiälä. In addition, the response of GPP and ET to the changes in environmental variables under severe water stress differed from those under other soil moisture conditions. The dominant reason is that low soil moisture leads to stomatal closure of the plants, which further limits plant carbon assimilation and transpiration. The consequence of decreased ET due to soil moisture

305 drought would be increased atmospheric VPD, which could in turn intensify stomatal closure (Eamus et al., 2013; Jarvis, 1976). Moreover, the GPP and ET were decoupled and EWUE decreased due to the soil moisture limitation. In contrast to EWUE, IWUE increased during the severe soil moisture drought at Hyytiälä. This means that the intrinsic water use efficiency at the ecosystem level was enhanced during soil moisture drought. uWUE was insensitive to the short-term soil moisture drought. Those findings indicate that IWUE is the most appropriate out of the three inspected metrics in capturing the impact

310 of soil moisture drought on plant functioning at the daily time scale. This is because that IWUE shows a clear signal in the days of the severe drought period and, through the VPD effect, is the most sensitive among the three metrics to stomatal closure. As uWUE is more independent of VPD, it probably is better suited to long-term studies where individual drought periods are not on the focus, but rather the impact of general environmental drivers (e.g., global warming and elevated atmosphere CO_2) on plant and ecosystem functioning.

315 **4.2 Differences between observations and site simulations**

The model showed the limitations on GPP and ET under the very dry soil moisture condition ($0 \leq$ SMI < 0.2) at Hyytiälä. However, the discrepancies in response between observed and simulated GPP and ET to changing environmental variables were obvious. This is because the formulation for stomatal conductance in JSBACH does not include air humidity, and therefore the stomatal conductance in JSBACH is insensitive to atmospheric VPD (Knauer et al., 2015). In Knauer et al.

320 (2015), Ball-Berry model (Ball et al., 1987) has been found to be best among a few stomatal conductance models in its response to atmospheric drought under non-limited soil moisture conditions. In reality, low soil moisture and high T_a during drought are closely coupled with high atmospheric VPD. Our results indicate that the combined effects of soil moisture and atmospheric drought on stomatal conductance have to be taken into account. Moreover, model performance could be improved through the inclusion of non-stomatal limitations on plant photosynthesis, which have been considered to be important for the

325 simulation of short-term plant responses to drought (Egea et al., 2011; Manzoni et al., 2011; Zhou et al., 2013). However, JSBACH is being continuously developed and the effect of soil water stress is to be accounted according to Egea et al., 2011 for both stomatal and non-stomatal processes, affecting both conductance and photosynthesis parameters.

Moreover, when comparing results from the EC data and simulations, it should be kept in mind that the EC method has its

330 uncertainties. Due to the stochastic nature of the turbulent flow, there is always a random error component in the observations. In addition, imperfect spectral corrections and gap-filling procedures as well as calibration problems may be sources of

systematic errors (Richardson et al., 2012; Wilson et al., 2002). The uncertainty of EC flux data is typically 20-30% for annual carbon budget (Aubinet et al., 2012; Baldocchi, 2003). Nevertheless, the uncertainties of the GPP and ET estimated from EC measurements are likely to have negligible impacts on our findings of the three WUE metrics, as the same data with the same uncertainties were used.

5. Conclusions

In this study, the impact of the severe soil moisture drought in the summer of 2006 on the water use efficiency of a boreal scots pine forest ecosystem at Hyytiälä flux site in southern Finland was investigated using both ground-based observations from a flux tower and the site-level simulation by the JSBACH land surface model. The soil moisture index (SMI) was used to indicate the soil moisture condition at the site. Finland is a high-latitude country and drought is uncommon. The summer drought in 2006 caused severe forest damage in southern Finland (Muukkonen et al., 2015). The SMI calculated from regional soil moisture simulations over the past 30 years (1981-2010) indicated that such extreme drought affecting forest health was rare in Finland, and the summer drought in 2006 in southern Finland was the most severe one in the 30-year study period (Gao et al., 2016). According to climate scenarios, regardless of the anticipated increase of precipitation, a modest drying of soil is foreseen in the Northern-Europe during the 21st century because of intensifying evapotranspiration (Ruosteenoja et al., 2017).

The impacts from the severe soil moisture drought on plant functioning at the site were clearly seen in the gross primary production (GPP) and evapotranspiration (ET). From both observation and simulation results, the GPP and ET reached the recorded minimums during the drought event. Through the comparison of the three investigated water use efficiency metrics (EWUE, IWUE and uWUE), the inherent water use efficiency (IWUE) was found to be the best in capturing the impact of soil moisture drought on plant functioning at the daily time scale. IWUE is inversely related to stomatal closure at the ecosystem level, and showed a clear signal in the days of the severe drought period. The increase of IWUE indicates that the intrinsic water use efficiency at the ecosystem level was enhanced. The ecosystem water use efficiency (EWUE) was too sensitive to the changes of GPP and ET. The underlying water use efficiency (uWUE) is considered to be more suitable for long-term studies of the impacts from general environment changes on plant functioning rather than the short-term sporadic drought event, because uWUE is more independent of VPD and was insensitive to the severe soil moisture drought.

The simulated response in plant functioning to the severe soil moisture drought predicted by JSBACH was weaker than those in the observed dataset, even though the strong limitation on GPP and ET through stomatal closure were seen at the very dry soil moisture condition ($0 \leq$ SMI < 0.2) as in the observed data. This illustrates that the the stomatal conductance was less reduced in the model during the drought event. The main reason for the differences between the observed and the model results is that the stomatal conductance model in JSBACH is insensitive to air humidity. This suggests that combined formulations of atmospheric and soil moisture drought are needed in the model to adequately simulate effects of drought on plant functioning. In addition, inclusion of non-stomatal limitations on photosynthesis during drought, e.g., reduced mesophyll conductance or carboxylation capacity, may also lead to an improvement of the model results (Keenan et al., 2010).

This study gives a view of the response of boreal forests to summer drought, and further suggests that choosing the appropriate

indicator, and improving our knowledge of ecosystem processes in land surface models are of great importance when
370 estimating biosphere-atmosphere feedbacks of terrestrial ecosystems under climate change.

References

Arneth, A., Veenendaal, E. M., Best, C., Timmermans, W., Kolle, O., Montagnani, L., and Shibistova, O.: Water use strategies and ecosystem-atmosphere exchange of CO_2 in two highly seasonal environments, Biogeosciences, 3, 421-437, doi:10.5194/bg-3-421-2006, 2006.

380 Aubinet, M., Vesala, T., and Papale, D.: Eddy covariance: a practical guide to measurement and data analysis, Springer Science & Business Media, Netherlands, 2012.

Aurela M., Lohila A., Tuovinen J.-P., Hatakka J., Penttilä T., and Laurila T.: Carbon dioxide and energy flux measurements in four northern-boreal ecosystems at Pallas. Boreal Env. Res., 20, 455–473, 2015.

Aurela, M.: Carbon dioxide exchange in subarctic ecosystems measured by a micrometeorological technique, Contributions,
385 51, Finnish Meteorological Institute, Helsinki, Finland, 132 pp., 2005.

Baldocchi, D. D.: Assessing the eddy covariance technique for evaluating carbon dioxide exchange rates of ecosystems: past, present and future, Global Change Biology, 9, 479-492, 2003.

Ball, J. T., Woodrow, I. E. , and Berry, J. A.: A model predicting stomatal conductance and its contribution to the control of photosynthesis under different environmental conditions, Progress in Photosynthesis Research, J. Biggins (Editor), Springer
390 Netherlands, Dordrecht, Netherlands, 221–224, 1987.

Beer, C., Ciais, P., Reichstein, M., Baldocchi, D., Law, B. E., Papale, D., Soussana, J. F., Ammann, C., Buchmann, N., Frank, D., Gianelle, D., Janssens, I. A., Knohl, A., Köstner, B., Moors, E., Roupsard, O., Verbeeck, H., Vesala, T., Williams, C. A., and Wohlfahrt, G.: Temporal and among-site variability of inherent water use efficiency at the ecosystem level, Global Biogeochemical Cycles, 23, 2009.

395 Berry, J. A., Beerling, D. J., and Franks, P. J.: Stomata: key players in the earth system, past and present, Current opinion in plant biology, 13, 232-239, 2010.

Betts, A. K.: Understanding Hydrometeorology Using Global Models, Bulletin of the American Meteorological Society, 85, 1673-1688, 2004.

Böttcher K., Markkanen, T., Thum, T., Aalto, T., Aurela, M., Reick, C. H., Kolari, P., Arslan, A. N., and Pulliainen. J.:
400 Evaluating biosphere model estimates of the start of the vegetation active season in boreal forests by satellite observations, 8, 580, doi:10.3390/rs8070580, Remote Sens., 2016.

Bréda, N., Cochard, H., Dreyer, E., and Granier, A.: Water transfer in a mature oak stand (Quercus petraea): seasonal evolution and effects of a severe drought, Canadian Journal of Forest Research, 23, 1136-1143, 1993.

Clenciala, E., Kucera, J., Ryan, M., G., and Lindroth, A.: Water flux in boreal forest during two hydrologically contrasting
405 years; species specific regulation of canopy conductance and transpiration, Ann. For. Sci., 55, 47-61, 1998.

Collatz, G., Ribas-Carbo, M., and Berry, J.: Coupled photosynthesis-stomatal conductance model for leaves of C4 plants, Australian Journal of Plant Physiology, 19, 519-538, 10.1071/PP9920519, 1992.

Cowan, I. R. and Farquhar, G. D.: Stomatal function in relation to leaf metabolism and environment, Symp. Soc. Exp. Biol., 31, 471-505, 1977.

410 Eamus, D., Boulain, N., Cleverly, J., and Breshears, D. D.: Global change-type drought-induced tree mortality: vapor pressure

deficit is more important than temperature per se in causing decline in tree health, Ecology and Evolution, 3, 2711-2729, 2013.

Egea, G., Verhoef, A., and Vidale, P. L.: Towards an improved and more flexible representation of water stress in coupled photosynthesis–stomatal conductance models, Agricultural and Forest Meteorology, 151, 1370-1384, 2011.

FAO-UNESCO: Soil map of the world: Revised legend. World Soil Resources Report 60, FAO, Rome, 1990.

415   Farquhar, G., O'Leary, M., and Berry, J.: On the Relationship Between Carbon Isotope Discrimination and the Intercellular Carbon Dioxide Concentration in Leaves, Functional Plant Biology, 9, 121-137, 1982.

Farquhar, G. D., Caemmerer, S., and Berry, J. A.: A biochemical model of photosynthetic CO_2 assimilation in leaves of C3 species, Planta, 149, 78-90, 1980.

420   Gao, Y., Markkanen, T., Thum, T., Aurela, M., Lohila, A., Mammarella, I., Kämäräinen, M., Hagemann, S., and Aalto, T.: Assessing various drought indicators in representing summer drought in boreal forests in Finland, Hydrol. Earth Syst. Sci., 20, 175-191, 2016.

Ge, Z.-M., Kellomaki, S., Zhou, X., and Peltola, H.: The role of climatic variability in controlling carbon and water budgets in a boreal Scots pine forest during ten growing seasons, Boreal environment research, 19, 181-195, 2014.

Guo, D., Westra S., and Maier H. R.: An R package for modelling actual, potential and reference evapotranspiration, 425   Environmental Modelling & Software, 78, 216-224, 2016.

Granier, A., Bréda, N., Longdoz, B., Gross, P., and Ngao, J.: Ten years of fluxes and stand growth in a young beech forest at Hesse, North-eastern France, Ann. For. Sci., 65, 704, 2008.

Granier, A., Reichstein, M., Bréda, N., Janssens, I. A., Falge, E., Ciais, P., Grünwald, T., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Facini, O., Grassi, G., Heinesch, B., Ilvesniemi, H., Keronen, P., Knohl, A., Köstner, B., Lagergren, F., 430   Lindroth, A., Longdoz, B., Loustau, D., Mateus, J., Montagnani, L., Nys, C., Moors, E., Papale, D., Peiffer, M., Pilegaard, K., Pita, G., Pumpanen, J., Rambal, S., Rebmann, C., Rodrigues, A., Seufert, G., Tenhunen, J., Vesala, T., and Wang, Q.: Evidence for soil water control on carbon and water dynamics in European forests during the extremely dry year: 2003, Agricultural and Forest Meteorology, 143, 123-145, 2007.

Hagemann, S. and Stacke, T.: Impact of the soil hydrology scheme on simulated soil moisture memory, Climate Dynamics, 435   44, 1731-1750, 2015.

Hari, P. and Kulmala, M.: Station for Measuring Ecosystem–Atmosphere Relations (SMEAR II), Boreal Env. Res., 10, 315–322, 2005.

Hillel, D.: Environmental Soil Physics, Academic Press, San Diego, 1998.

Huang, M., Piao, S., Sun, Y., Ciais, P., Cheng, L., Mao, J., Poulter, B., Shi, X., Zeng, Z., and Wang, Y.: Change in terrestrial 440   ecosystem water-use efficiency over the last three decades, Global Change Biology, 21, 2366-2378, 2015.

Ilvesniemi, H., Pumpanen, J., Duursma, R., Hari, P., Keronen, P., Kolari, P., Kulmala, M., Mammarella, I., Nikinmaa, E., Rannik, U., Pohja, T., Siivola, E., and Vesala, T.: Water balance of a boreal Scots pine forest, Boreal Environment Research, 15, 375-396. 2010.

Irvine, J., Perks, M. P., Magnani, F., and Grace, J.: The response of Pinus sylvestris to drought: stomatal control of 445   transpiration and hydraulic conductance, Tree Physiology, 18, 393-402, 1998.

Jarvis, P.: The interpretation of the variations in leaf water potential and stomatal conductance found in canopies in the field, Philosophical Transactions of the Royal Society of London B: Biological Sciences, 273, 593-610, 1976.

Jung, M., Maire, G. L., Zaehle, S., Luyssaert, S., Vetter, M., Churkina, G., Ciais, P., Viovy, N., and Reichstein, M.: Assessing the ability of three land ecosystem models to simulate gross carbon uptake of forests from boreal to Mediterranean climate in 450   Europe, Biogeosciences, 4, 647-656, 2007.

Keenan, T. F., Hollinger, D. Y., Bohrer, G., Dragoni, D., Munger, J. W., Schmid, H. P., and Richardson, A. D.: Increase in forest water-use efficiency as atmospheric carbon dioxide concentrations rise, Nature, 499, 324-327, 2013.

Keenan, T., Sabate, S., and Gracia, C.: Soil water stress and coupled photosynthesis–conductance models: Bridging the gap between conflicting reports on the relative roles of stomatal, mesophyll conductance and biochemical limitations to 455   photosynthesis, Agricultural and Forest Meteorology, 150, 443-453, 2010.

Knauer, J., Werner, C., and Zaehle, S.: Evaluating stomatal models and their atmospheric drought response in a land surface scheme: A multibiome analysis, Journal of Geophysical Research: Biogeosciences, 120, 1894-1911, 2015.

Knorr, W.: Annual and interannual CO_2 exchanges of the terrestrial biosphere: process-based simulations and uncertainties,

Global Ecology and Biogeography, 9, 225-252, 2000.

460   Kolari, P., Kulmala, L., Pumpanen, J., Launiainen, S., Ilvesniemi, H., Hari, P., and Nikinmaa, E.: CO_2 exchange and component CO_2 fluxes of a boreal Scots pine forest, Boreal Environment Research, 14, 761-783, 2009.

Law, B. E., Falge, E., Gu, L., Baldocchi, D. D., Bakwin, P., Berbigier, P., Davis, K., Dolman, A. J., Falk, M., Fuentes, J. D., Goldstein, A., Granier, A., Grelle, A., Hollinger, D., Janssens, I. A., Jarvis, P., Jensen, N. O., Katul, G., Mahli, Y., Matteucci, G., Meyers, T., Monson, R., Munger, W., Oechel, W., Olson, R., Pilegaard, K., Paw U, K. T., Thorgeirsson, H., Valentini, R., 465   Verma, S., Vesala, T., Wilson, K., and Wofsy, S.: Environmental controls over carbon dioxide and water vapor exchange of terrestrial vegetation, Agricultural and Forest Meteorology, 113, 97-120, 2002.

Lloyd, J. O. N., Shibistova, O., Zolotoukhine, D., Kolle, O., Arneth, A., Wirth, C., Styles, J. M., Tchebakova, N. M., and Schulze, E. D.: Seasonal and annual variations in the photosynthetic productivity and carbon balance of a central Siberian pine forest, Tellus B, 54, 590-610, 2002.

470   Lloyd, J. and Farquhar, G.D.: ^{13}C discrimination during CO_2 assimilation by the terrestrial biosphere, Oecologia, 99, 201-215, doi:10.1007/BF00627732, 1994.

Mammarella, I., Peltola, O., Nordbo, A., Järvi, L., and Rannik, Ü., 2016. Quantifying the uncertainty of eddy covariance fluxes due to the use of different software packages and combinations of processing steps in two contrasting ecosystems, Atmos. Meas. Tech., 9, 4915-4933, doi:10.5194/amt-9-4915-2016.

475   Mammarella, I., Kolari, P., Rinne, J., Keronen, P., Pumpanen, J. and Vesala, T.: Determining the contribution of vertical advection to the net ecosystem exchange at Hyytiälä forest, Finland, Tellus B, 59, 900-909, doi:10.1111/j.1600-0889.2007.00306.x, 2007.

Manzoni, S., Vico, G., Katul, G., Fay, P. A., Polley, W., Palmroth, S., and Porporato, A.: Optimizing stomatal conductance for maximum carbon gain under water stress: a meta-analysis across plant functional types and climates, Functional Ecology, 480   25, 456-467, 2011.

Markkanen, T., Rannik, U., Keronen, P., Suni, T., and Vesala, T.: Eddy covariance fluxes over a boreal Scots pine forest, Boreal environment research, 6, 65-78, 2001.

McDowell, N., Pockman, W. T., Allen, C. D., Breshears, D. D., Cobb, N., Kolb, T., Plaut, J., Sperry, J., West, A., Williams, D. G., and Yepez, E. A.: Mechanisms of plant survival and mortality during drought: why do some plants survive while others 485   succumb to drought?, New Phytologist, 178, 719-739, 2008.

Muukkonen, P., Nevalainen, S., Lindgren, M., and Peltoniemi, M.: Spatial Occurrence of Drought-Associated Damages in Finnish Boreal Forests: Results from Forest Condition Monitoring and GIS Analysis, Boreal Environ. Res., 20, 172–180, 2015.

Nemani, R. R., Keeling, C. D., Hashimoto, H., Jolly, W. M., Piper, S. C., Tucker, C. J., Myneni, R. B., and Running, S. W.: 490   Climate-Driven Increases in Global Terrestrial Net Primary Production from 1982 to 1999, Science, 300, 1560-1563, 2003.

Raddatz, T. J., Reick, C. H., Knorr, W., Kattge, J., Roeckner, E., Schnur, R., Schnitzler, K. G., Wetzel, P., and Jungclaus, J.: Will the tropical land biosphere dominate the climate–carbon cycle feedback during the twenty-first century?, Climate Dynamics, 29, 565-574, 2007.

Reichstein, M., Ciais, P., Papale, D., Valentini, R., Running, S., Viovy, N., Cramer, W., Granier, A., OgÉE, J., Allard, V., 495   Aubinet, M., Bernhofer, C., Buchmann, N., Carrara, A., GrÜNwald, T., Heimann, M., Heinesch, B., Knohl, A., Kutsch, W., Loustau, D., Manca, G., Matteucci, G., Miglietta, F., Ourcival, J. M., Pilegaard, K., Pumpanen, J., Rambal, S., Schaphoff, S., Seufert, G., Soussana, J. F., Sanz, M. J., Vesala, T., and Zhao, M.: Reduction of ecosystem productivity and respiration during the European summer 2003 climate anomaly: a joint flux tower, remote sensing and modelling analysis, Global Change Biology, 13, 634-651, 2007.

500   ., Pumpanen, J., Reick, C. H., Raddatz, T., Brovkin, V., and Gayler, V.: Representation of natural and anthropogenic land cover change in MPI-ESM, Journal of Advances in Modeling Earth Systems, 5, 459-482, 2013.

Richardson, A. D., Aubinet, M., Barr, A. G., Hollinger, D. Y., Ibrom, A., Lasslop, G., and Reichstein, M.: Uncertainty Quantification. In: Eddy Covariance: A Practical Guide to Measurement and Data Analysis, Aubinet, M., Vesala, T., and Papale, D. (Eds.), Springer Netherlands, Dordrecht, 2012.

505   Roeckner, E., Arpe, K., Bengtsson, L., Christoph, M., Claussen, M., Dümenil, L., Esch, M., Giogetta, M., Schlese, U., and Schultz-Weida, U.: The atmospheric general circulation model ECHAM4: Model description and simulation of the present-day climate, Max Planck Institute for Meterology, Hamburg, 1996.

Roeckner, E., Bäuml, G., Bonaventura, L., Brokopf, R., Esch, M., Giorgetta, M., Hagemann, S., Kirchner, I., Kornblueh, L., and Manzini, E.: The atmospheric general circulation model ECHAM5. PART I: Model description. MPI for meteorology, Hamburg, Germany, 2003.

510

Ruosteenoja, K., Markkanen, T., Venäläinen, A., Räisänen, P. and Peltola, H.: Seasonal soil moisture and drought occurrence in Europe in CMIP5 projections for the 21st century, Climate Dynamics, 1-16, 2017, doi:10.1007/s00382-017-3671-4.

Schulze, E.-D., Beck, E., and Müller-Hohenstein, K.: Plant Ecology, Springer-Verlag Berlin Heidelberg, 2005.

Seneviratne, S. I., Corti, T., Davin, E. L., Hirschi, M., Jaeger, E. B., Lehner, I., Orlowsky, B., and Teuling, A. J.: Investigating

515   soil moisture–climate interactions in a changing climate: A review, Earth-Science Reviews, 99, 125-161, 2010.

Stevens, B., Giorgetta, M., Esch, M., Mauritsen, T., Crueger, T., Rast, S., Salzmann, M., Schmidt, H., Bader, J., Block, K., Brokopf, R., Fast, I., Kinne, S., Kornblueh, L., Lohmann, U., Pincus, R., Reichler, T., and Roeckner, E.: Atmospheric component of the MPI-M Earth System Model: ECHAM6, Journal of Advances in Modeling Earth Systems, 5, 146-172, 2013.

Vesala, T., Suni, T., Rannik, Ü., Keronen, P., Markkanen, T., Sevanto, S., Grönholm, T., Smolander, S., Kulmala, M.,

520   Ilvesniemi, H., Ojansuu, R., Uotila, A., Levula, J., Mäkelä, A., Pumpanen, J., Kolari, P., Kulmala, L., Altimir, N., Berninger, F., Nikinmaa, E., and Hari, P.: Effect of thinning on surface fluxes in a boreal forest, Global Biogeochemical Cycles, 19, 2005.

Will, R. E., Wilson, S. M., Zou, C. B., and Hennessey, T. C.: Increased vapor pressure deficit due to higher temperature leads to greater transpiration and faster mortality during drought for tree seedlings common to the forest–grassland ecotone, New Phytologist, 200, 366-374, 2013.

525   Wilson, K., Goldstein, A., Falge, E., Aubinet, M., Baldocchi, D., Berbigier, P., Bernhofer, C., Ceulemans, R., Dolman, H., Field, C., Grelle, A., Ibrom, A., Law, B. E., Kowalski, A., Meyers, T., Moncrieff, J., Monson, R., Oechel, W., Tenhunen, J., Valentini, R., and Verma, S.: Energy balance closure at FLUXNET sites, Agricultural and Forest Meteorology, 113, 223-243, 2002.

Wolf, S., Eugster, W., Ammann, C., Häni, M., Zielis, S., Hiller, R., Stieger, J., Imer, D., Merbold, L., and Buchmann, N.:

530   Contrasting response of grassland versus forest carbon and water fluxes to spring drought in Switzerland, Environmental Research Letters, 8, 035007, 2013.

Zhou, S., Duursma, R. A., Medlyn, B. E., Kelly, J. W. G., and Prentice, I. C.: How should we model plant responses to drought? An analysis of stomatal and non-stomatal responses to water stress, Agricultural and Forest Meteorology, 182–183, 204-214, 2013.

535   Zhou, S., Yu, B., Huang, Y., and Wang, G.: Daily underlying water use efficiency for AmeriFlux sites. J. Geophys. Res. Biogeosci., 120, 887–902. doi: 10.1002/2015JG002947, 2015.

Zhou, S., Yu, B., Huang, Y., and Wang G.: The effect of vapor pressure deficit on water use efficiency at the subdaily time scale, Geophys. Res. Lett., 41, 5005–5013, doi:10.1002/2014GL060741, 2014.
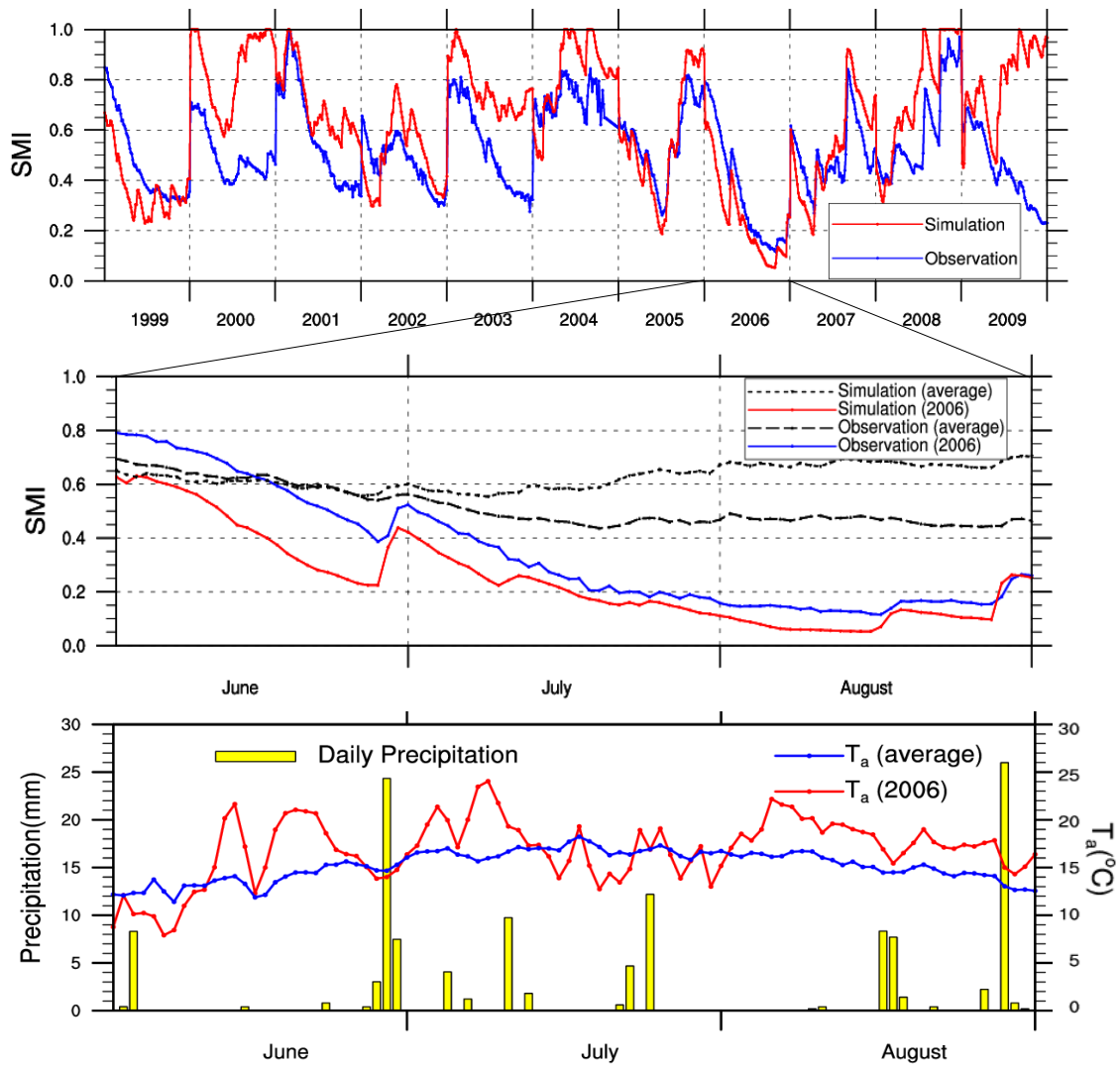
Figure 1: (a) Daily mean soil moisture index (SMI) at Hyytiälä from observation and the JSBACH simulation for the summer months (June, July, August) in the 11-year study period (from 1999 to 2009). (b) Daily mean SMI at Hyytiälä from observation and the JSBACH simulation for the summer months in 2006; The two black dashed lines represent the averaged daily SMI in the summer months over the 11-year study period from observation and the JSBACH simulation. (c) Daily mean air temperature (T_a) in the summer months of 2006 and the averaged daily mean T_a in the summer months over the 11-year study period at Hyytiälä from observation, meanwhile, the daily precipitation amount in 2006 is shown as bar plot.
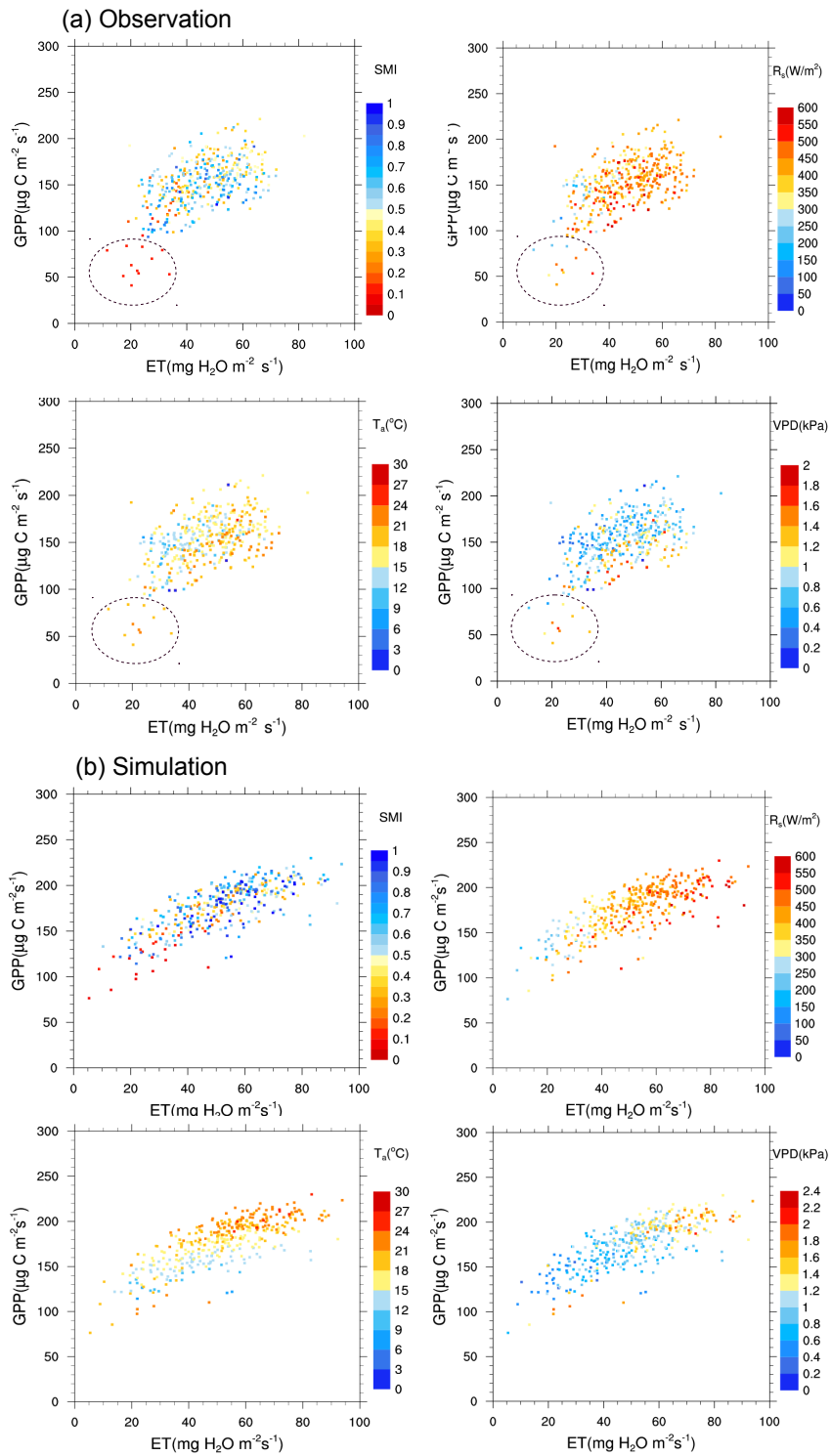
Figure 2: **Relationship between** the daytime averaged **gross primary production (GPP** in µg C m^{-2}s^{-1}**) and evapotranspiration (ET** in mg H$_2$O m^{-2} s^{-1}**) at Hyytiälä in the summer months (June, July, August) of the 11-year study period (from 1999 to 2009) from (a) observation and (b) the JSBACH simulation.** **Data are categorized according to** daily mean **soil moisture index (SMI),** daytime mean incoming shortwave **radiation (R$_s$),** daytime mean **air temperature (T$_a$) and** daytime mean **vapour pressure deficit (VPD**), respectively.
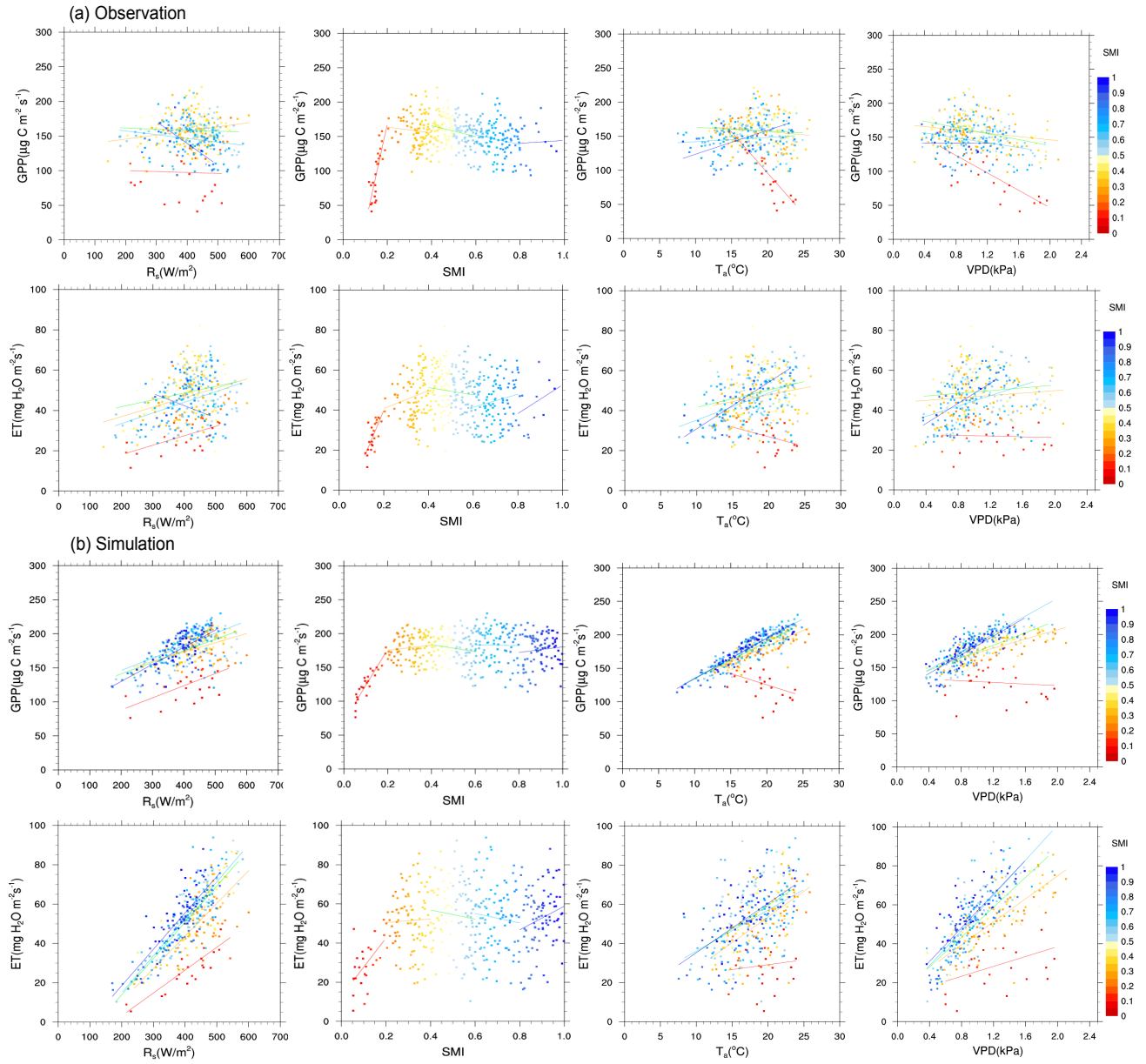
Figure 3: Response of daytime mean gross primary production (GPP in µg C m^{-2}s^{-1}) and evapotranspiration (ET in mg H$_2$O m^{-2} s^{-1}) to daytime mean incoming shortwave radiation (R$_s$), daytime mean air temperature (T$_a$), daytime mean vapour pressure deficit (VPD), and daily mean soil moisture index (SMI) at Hyytiälä, categorized by daily mean soil moisture index (SMI) in the summer months (June, July, August) of the 11-year study period (from 1999 to 2009) from (a) observation and (b) the JSBACH simulation. The regression lines are fitted for the five SMI groups (very dry: 0 ≤ SMI < 0.2, moderate dry: 0.2 ≤ SMI < 0.4, mid-range: 0.4 ≤ SMI < 0.6, moderate wet: 0.6 ≤ SMI < 0.8, very wet: 0.8 ≤ SMI <1).
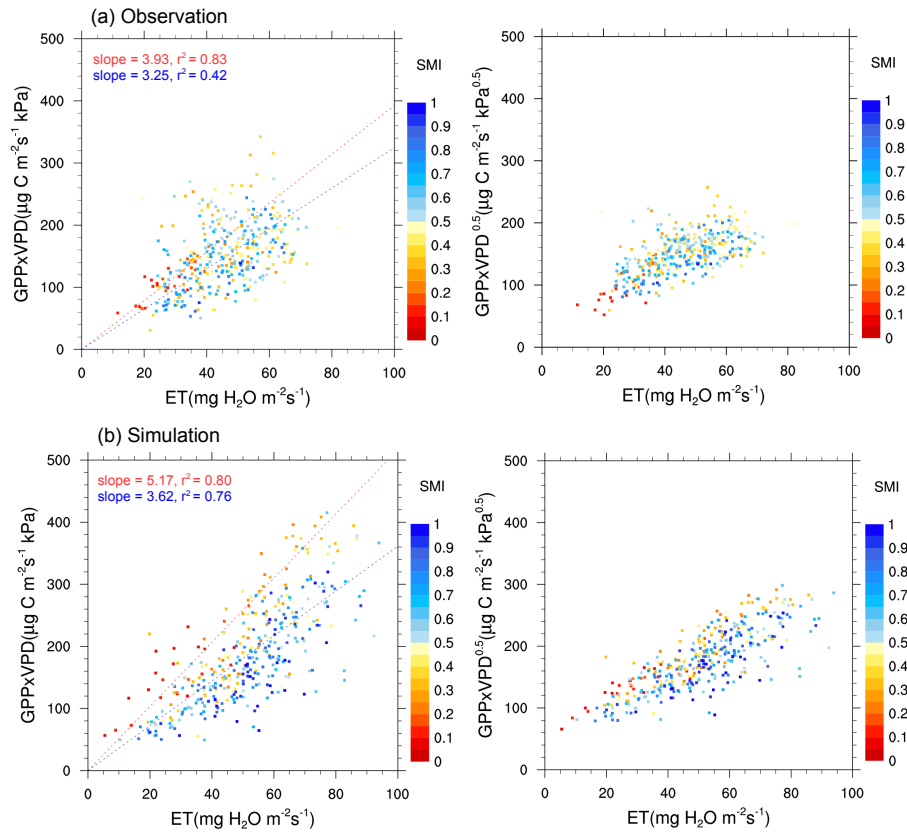
Figure 4: The dependence of the product of daytime mean gross primary production (GPP in μg C m^{-2}s^{-1}) and daytime mean vapour pressure deficit (VPD) on evapotranspiration (ET in mg H$_2$O m^{-2} s^{-1}) (i.e., GPP×VPD/ET, which represents the inherent water use efficiency (IWUE)), and the dependence of the production of GPP and the square root of VPD on ET (i.e., GPP×VPD$^{0.5}$/ET, which represents the underlying water use efficiency (uWUE)) in the summer months (June, July, August) of the 11-year study period (from 1999 to 2009) from (a) observation and (b) the JSBACH simulation. Data are categorized according to daily mean soil moisture index (SMI). The fitted lines for the dependence of the product of GPP and VPD on ET are for the data under SMI < 0.2 (red line) and the data under 0.2 ≤ SMI <1 (blue line), respectively; both fittings are statistically significant (p-value < 0.05). No lines were fitted for the dependence of the production of GPP and the square root of VPD on ET, as the data under SMI < 0.2 and data under 0.2 ≤ SMI <1 are more converged in a line in comparison to the dependence of the product of GPP and VPD on ET.

580

Table 1: Key characteristics relevant to this study from observation and the parameter settings in the JSBACH site level simulation at Hyytiälä site.

Observation								
Site	Location	Vegetation type	LAI (m²/m²) (all-sided, annual)	Canopy height (m)	Measurement height (m)	Annual mean air temperature (°C) and precipitation (mm) (30-year averages)	Soil type	Analysed measurement depth of soil moisture (cm)	References
Hyytiälä	61°51'N, 24°17'E	Scots pine	6	13-16	23	2.9; 709	Mineral (Haplic podzol)	−5 to −23; −23 to −60	Markkanen et al.(2001); Vesala et al. (2005)

Settings in JSBACH							
Site	PFT	Maximum LAI (m²/m²)	Maximum electron transport rate (Vmax) at 25 °C	Maximum carboxylation rate at 25 °C	Soil type	Analysed depth of soil moisture (cm)	Soil depth (m)	Root depth (m)
Hyytiälä	Evergreen needleleaf forest	16	37.5	71.3	Loamy sand	Average of layer-2 (6.5–31.9) and layer-3 (31.9–123.2)	5.416	1.265