point-by-point response to the reviews

Reply to Anonymous Referee #5

General comments:

The authors did a good job improving over the original submission. They dealt well with most of the comments raised on earlier review. However, the manuscript contains many language errors and I recommend that it carefully be edited by a native English speaker. Some are listed below in the minor comments but the list is by no means exhaustive. Also where graphs share the same y-axis title and y-axis label, the readability of the graphs could be enhanced by using only one (on the left hand side) y-axis title and y-axis label instead of having them for each panel (for example, Figs. 2 and 3).

I recommend accept with minor revision.

Authors response (AR): We appreciate the reviewer's detailed and helpful comments. In the revised version, we have tried to correct language errors listed below and in some other places. The graphs sharing the same y-axis title and y-axis label have been replotted, using only one y-axis title and y-axis label.

Minor revisions to consider:

Lines 71–72: Not sure what message this sentence is meant to convey?

AR: We have reformulated this sentence as "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 and proposed the ecosystem level inherent water use efficiency (IWUE), which is a quantity defined as EWUE multiplied with mean daytime VPD." to introduce IWUE.

Lines 76–77: 'The appropriateness of uWUE at daily time scale was also demonstrated (Zhou et al., 2015).'??

AR: We have revised the sentence according to reviewer's suggestion.

Lines 87–88: ??… (3) to evaluate how adequately the JSBACH land surface model (LSM) captures plant responses to changes in environmental variables.??

AR: We have modified this sentence according to reviewer's suggestion.

Line 95: Check LAI in Table 1.

AR: Yes, we have checked the LAI values in Table 1. There was no mistake of the LAI values in Table 1. To clarify, we added explanation about the maximum LAI set in JSBACH in the manuscript as " The modelled LAI reached values close to the observed LAI when the parameter maximum LAI was set to $16\ m^2/m^2$ ".

Line 96: '+' is not necessary.

AR: We have deleted '+'.

Line 107: ' … by excluding …'

AR: We have added 'by' in here.

Lines 120–121: Move this to line 193 to explain why the first layer was not included in the analysis.

AR: We have added this reason in line 193.

Line 215: Perhaps present some measure of variation (e.g. standard deviation, confidence interval, etc) in addition to averages in the 11-year climatic conditions so that readers could have an idea of the deviations during the drought period.

AR: We have provided the standard deviation in addition to averages in the 11-year climate conditions in the text.

Lines 222 and 224: Coefficient of determination was used elsewhere; no need to put the numbers in brackets; is three significant digits necessary here?; what is the difference between correlation coefficient and time correlation?.

AR: We have used correlation coefficient in all the places in the revised manuscript. We agree that there is no need to put the numbers in brackets and we have changed this. We changed three significant digits for correlation coefficients to two significant digits. There was no difference between correlation coefficient and time correlation in what we were trying to mean there. For clarity, we changed time correlation to correlation coefficient.

Line 225: Replace 'was' with 'being'

AR: 'was' have been replaced with 'being'.

Line 228: Replace 'presented' with 'observed'

AR: Yes, we have replaced 'presented' with 'observed'.

Line 230: Replace 'is' with 'was'

AR: This error has been corrected.

Line 232–233: Please reword the sentence 'The biggest difference of 1.054 kPa took place on August 5th, the day with highest Ta in August 2006.'

AR: We have reworded the sentence as "The biggest difference between the daily mean VPD and the 11-year averaged daily mean VPD reached 1.054 kPa on August 5th that was the day with highest T_a in August 2006." to make it more clear.

Line 266: Replace 'environment' with 'environmental'

AR: We have replaced 'environment' with 'environmental'.

Lines 291–292: Provide units; the SMI values for the IWUE values are swapped??

AR: We have provided the units for IWUE here and corrected the mistake on the swapped SMI values.

Reply to Referee #6

The authors responded well to the comments arisen. A minor concern, I suggest arranging the content of Discussion and Conclusion sections. I prefer a brief and clear conclusion with the key finding of the study, however, the current Conclusion is uneasy for the readers to understand the highlights. I think the related discussion on mechanism of impacts of drought on different WUE types should be embedded into the Discussion sections.

Authors response (AR): We appreciate the comments from the reviewer. In the revised version, we have tried to rewrite the conclusion to be more focused on the key findings of the study. We hope the current conclusion is easy for the readers to understand the highlights.

Reply to Referee #7

In the first round of the review, the reviewers have addressed some important points (e.g. filtering of the data, focus on one site only, classification of SMI values etc.).
Most of these comments were adequately addressed by the authors, and the revised version of the manuscript has improved in many aspects. The Methods and Results sections are clearly and well written.
However, the discussion is weak and lacks novel aspects. In particular, I do not agree with the conclusion of IWUE being the most appropriate WUE metric, and I doubt that this question can be answered based on the results of this study. See more details below.

Authors response (AR): We appreciate the reviewer's constructive comments. In the current manuscript, we have revised the discussion and conclusion about water use efficiency metrics. Please see the details in the revised manuscript. We hope our revision solves the reviewer's concern.

More detailed comments:

- I think the introduction would be stronger if the authors mentioned the anticipated occurrence of drought in this region (e.g. after line 49). In the current version, this is only mentioned in the conclusions.

AR: We have added the anticipated occurrence of drought in this region in the revised manuscript.

- line 74: "simple stomatal model" does not adequately describe the model by Lloyd & Farquhar 1994. I suggest to reformulate this in a way that clarifies that it is based on the optimality theory developed by Cowan & Farquhar 1977.

AR: Yes, we have reformulated this sentence as "an optimality theory (Cowan and Farquhar, 1977) based stomatal model with the assumptions suggested by Farquhar et al. (1993) and Lloyd and Farquhar (1994)".

- I agree not to use layer 1 soil moisture, but the justification "too sensitive to climate variability" is a bit misleading as "climate" implies a longer time scale than what you mean here.

AR: We will modify the "climate variability" to "temperature and precipitation variations".

- line 165: replace "JSABCH" with "JSBACH"

AR: We have corrected this error.

- line 193f: not clear how these soil parameters were determined. Please explain shortly.

AR: The soil parameters are derived based on water retention curves determined from soil samples taken at the site. We have added this explanation in the manuscript.

- line 204f.: I would not introduce IWUE as a measure of surface conductance. This metric accounts for the confounding effects of VPD on ET, but it does not consider that also Gs decreases with increasing VPD (but uWUE does). Further, the derivation of IWUE is based on strong assumptions (e.g. that Ga is infinitely high) that are not justified when this metric is interpreted in terms of Gs. It's ok to use this metric, but the authors should not over-interpret its physiological meaning. I suggest to introduce it simply as a WUE metric that accounts for the effects of VPD on ET. For the same reasons, don't call IWUE "intrinsic WUE" in line 307

AR: We agree with the reviewer. Thus, we have deleted the places that introduce IWUE as a measure of surface conductance at the ecosystem level and as a representative of intrinsic WUE at the ecosystem level.

- line 207: cite Zhou et al. 2014 again here, who suggested this metric

AR: We have added Zhou et al. 2014 here in the revised manuscript.

- An interesting aspect of Figure 1 is that in some years (e.g. 2003, 2009), the simulated and observed soil water dynamics do not agree well compared to the other years. Do the authors have an explanation of why this could be the case?

AR: Indeed, we agree with the reviewer that there are some discrepancies between the simulated and observed soil water dynamics in some years. The soil water dynamics in the model show faster response to both lack of water supply as well as to precipitation events than the observations. Furthermore, deviations in the initial values of soil moisture after the snow melt in the beginning of the season impacts the soil moisture in the later season. Differences in the dynamics are not surprising as the model does not account for the vertical layering of the podzol soils and the model parameters are not calibrated with the measurement data. Regardless of the deviations in the dynamics, the model was able to produce both the timing and the spatial extent of the 2006 drought (Gao 2006).

- It would probably be too messy to show VPD in Figure 1 as well, but it would help to provide the absolute range of VPD observed in the drought period in the text, and not just the deviations compared to the reference period.

AR: We have added the mean value and standard deviation of VPD during the drought period in the

text.

- Lines 255f: this sentence is a bit unclear. Isn't it the other way around? I.e. the GPP-ET relationship is more linear in the simulations?

AR: We think the GPP-ET relationships are non-linear in both observation and simulation. To make it more clear, we have reformulated this sentence as "The non-linear relationship between the daytime averaged GPP and ET was also found in the JSBACH simulated result".

- I do not agree with most parts of section 4.1 (and the corresponding sections of the conclusions). The authors try to identify the most appropriate WUE efficiency measure, but they do not really explain why IWUE is considered more appropriate than the other metrics. Is it just because IWUE increased, whereas uWUE does not show a response to drought? That may be true but how do we know that this is then the more appropriate response? Another aspect that was not mentioned is that uWUE in Fig. 4 has a better correlation than IWUE. Isn't that an indication that uWUE is a better metric describing the water-carbon coupling? In my opinion, this part of the discussion lacks some more fundamental considerations of the metrics applied. For instance, uWUE was developed to overcome some shortcomings of the IWUE metric (i.e. the stomatal response to VPD is taken into account), and in that sense is a more meaningful metric to characterize ecosystem functioning than IWUE. The weaker VPD response of IWUE should also (or in particular) play a role in drought periods, so I don't follow the argumentation why uWUE should be better suited for long-term studies than for particular drought periods.

AR: We agree with the reviewer's comments. We revised the discussion in section 4.1 and concluded that the increase in IWUE during drought was a result of decreased stomatal conductance due to increased VPD. The uWUE was formulated to be more independent of a varying VPD than IWUE. The unchanged uWUE during this short-term drought demonstrated that the trade-off between carbon assimilation and water transpiration of the plants at this site was not disturbed by drought, even though the stomatal conductance decreased. We also agree with the reviewer that it is incorrect to state that uWUE is better suited to long-term studies where individual drought periods are not on the focus.

- other main points of the discussion are rather weak and repeat outcomes of earlier studies. For example, it is long known that stomatal conductance responds to air humidity. It is also commonly accepted that non-stomatal limitations are needed to adequately simulate the drought response in models. These aspects are long known to the modelling community.

AR: We agree that it is ideal that ecosystem models can have a very good representation of stomatal functioning and its dependence on VPD. Even though it is long known that stomatal conductance responses to air humidity and the non-stomatal limitation are needed, 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 been considered to be enough to account for drought effects. The performance of the default stomatal conductance model in JSBACH 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.

- Line 318: rewrite to "stomatal conductance in JSBACH does not include a response to air humidity" or simply delete the first part of the sentence.

AR: We have modified this sentence according to reviewer's suggestion.

- Figure 2a: Explain the meaning of the dashed circle also in the caption, not only in the text

AR: We have added the meaning of the dashed circle in the figure caption.

- Wouldn't it make more sense to present GPP in gC m-2 d-1? This would also be easier to interpret. Up to the authors.

AR: We agree that to present GPP in gC m^{-2} d^{-1} is easier to interpret. However, we selected the day time periods of effective photosynthesis with the criteria that incoming shortwave radiation (Rs) larger than 100 W/m^2. This means that we selected different time periods of different days. Thus, we think it is more proper here to use mean GPP and ET rates instead of daily sums here.

- Table 1: It would make sense to indicate the grain size distribution under "Soil type" in the lower part of the table.

AR: We tried to select the most reasonable soil type for the site level simulation to match with the soil type at the site. Nevertheless, there is no perfect match as we can only chose one soil type for the site in the model rather than mixed soil type in the reality. Unfortunately, there is no information on grain size distribution for the FAO soil types in the five layer soil hydrology scheme in JSBACH, which has been developed in Hagemann and Stacke (2015). There are only soil parameter values for the different FAO soil types which are taken from various sources. Interested reader can check those soil parameters for FAO soil types used in the five layer soil hydrology scheme in JSBACH from Hagemann and Stacke (2015).

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

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Abstract. The influence of drought on plant functioning has received considerable attention in recent years, however 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 based on IWUE and a simple stomatal model, is the ratio of GPP multiplied with a square root of VPD to ET) was unchanged during the drought. The decrease in EWUE was due to the stronger decline in GPP than in ET. The increase in IWUE was because of the decreased stomatal conductance under increased VPD. The unchanged uWUE indicates that the trade-off between carbon assimilation and transpiration of the boreal Scots pine forest was not disturbed by this drought event at the site. 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. 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. 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. Our study provides deeper understanding of coupling of carbon and water cycles in the boreal ecosystem Scots pine forests, 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 local environmental conditions and plant physiology (e.g., stomatal

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conductance; g_s). 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).

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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

70 symptoms in visual examination, in comparison to 2–4 % damaged sites in a normal year (Muukkonen et al. 2015). According to the simulated regional soil moisture, the summer drought in 2006 in southern Finland was the most severe one over the past 30 years (1981-2010), and the spatial distribution of the drought damages has been found to be closely related to the plant available soil moisture (Gao et al., 2016).

75 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 in close connection 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

80 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

85 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

90 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 and proposed

95 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 an optimality theory (Cowan and Farquhar, 1977) based stomatal model with the assumptions suggested by Farquhar et al. (1993) and Lloyd and Farquhar (1994), the underlying water use efficiency (uWUE) was 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 was found at the half-hourly time scale by Zhou et al. (2014). Later on, the appropriateness of uWUE at the daily time

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scale was also 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 the JSBACH land surface model (LSM) captures plant responses to changes in environmental variables.

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). 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 by 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.

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In addition to the EC measurements, a set of supporting meteorological variables were adopted as half-hourly averages; 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

155 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 of mineral soil (5 to 23 and 23 to 60 cm) at Hyytiälä was averaged over a day to represent 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 temperature and precipitation variations.

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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 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

165 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 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

170 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 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

175 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 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

180 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.

2.3.1 The stomatal conductance model in JSBACH

185 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.

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

190 calculated using the photosynthesis model in JSBACH, for which the intercellular CO_2 concentration under unstressed

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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 $C_{i,pot} = 0.87 C_a$ for C3 plants and $C_{i,pot} = 0.67 C_a$ for C4 plants (Knorr, 2000). After the $A_{n,pot}$ is determined, the $g_{s,pot}$ is derived using the following equation:

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

205 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:

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

where

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

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

2.4 Site level simulation by JSBACH

215 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 modelled LAI reached values close to the observed LAI when the parameter maximum LAI was set to 16 m^2/m^2. Also, the maximum carboxylation rate (Jmax) and maximum electron transport rate (Vmax) at 25 °C were adjusted, for the simulated

220 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 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.

225 **2.5 Soil Moisture Index (SMI)**

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):

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

where θ is the volumetric soil moisture [m^3 H$_2$O m^{-3}], θ_{FC} is the field capacity [m^3 H$_2$O m^{-3}] and θ_{WILT} is the permanent wilting point [m^3 H$_2$O m^{-3}]. When θ exceeds θ_{FC}, soil water cannot be retained against gravitational drainage, while below θ_{WILT}, the

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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: $0 \leq \text{SMI} < 0.2$, moderate dry: $0.2 \leq \text{SMI} < 0.4$, mid-range: $0.4 \leq \text{SMI} < 0.6$, moderate wet: $0.6 \leq \text{SMI} < 0.8$, very wet: $0.8 \leq \text{SMI} < 1$.

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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 the simulated SMI for Hyytiälä, for the aim to correspond with the observed SMI that calculated with measured soil moisture at the two lower levels of mineral soil at the site. The layer 1 soil moisture was excluded in determining both simulated and observed SMIs because it is too sensitive to temperature and

245 precipitation variations. For the observed SMI, the measured soil parameters derived based on water retention curves determined from soil samples taken at the site were adopted (i.e., volumetric soil moisture at saturation (θ_{SAT}) = 0.50 m^3 H$_2$O m^{-3}, θ_{FC} = 0.30 m^3 H$_2$O m^{-3} and θ_{WILT} = 0.08 m^3 H$_2$O m^{-3}). As θ_{FC} acts as a proxy for θ_{SAT} in the five layer soil hydrology scheme in JSBACH (Hagemann and Stacke, 2015), θ_{SAT} was used instead of θ_{FC} for consistency when calculating SMI based on the observed soil moisture data.

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

The ecosystem level water use efficiency is calculated as,

255 $$\text{EWUE} = \text{GPP/ET}, \tag{5}$$

IWUE is defined as EWUE multiplied by daytime mean VPD in Beer et al. (2009),

$$\text{IWUE} = \text{GPP} \times \text{VPD/ET}, \tag{6}$$

uWUE is derived based on IWUE and an optimality theory (Cowan and Farquhar, 1977) based stomatal model with the assumptions suggested by Farquhar et al. (1993) and Lloyd and Farquhar (1994) in Zhou et al. (2014). The formulation of

260 uWUE is,

$$\text{uWUE} = \text{GPP} \times \text{VPD}^{0.5}/\text{ET} \tag{7}$$

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

265 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

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

270 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

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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 of 0.63 and a root-mean-square error (RMSE) of 0.23. 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 correlation coefficient of 0.97 between simulated and observed SMIs were found for year 2006 (Fig. 1 (b)), despite the simulated SMI being systematically lower than the observed SMI (RMSE = 0.12).

Concurrently with the low soil moisture, a high T_a anomaly was observed 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 mean T_a in August 2006 (18.1 ± 1.9 °C) was 3.1 °C higher than that of the 11-year average (15.0 ± 1.63 °C). Also, the daily mean VPD in August 2006 was higher than the 11-year averaged daily mean VPD in August in general (not shown), except on the days with precipitation. Especially, the mean value of the daily mean VPD in the period from 31 July to 16 August (1.067 ± 0.361 kPa) was substantially higher than the mean of the 11-year averaged daily mean VPD over this period (0.582 ± 0.200 kPa). The biggest difference between the daily mean VPD and the 11-year averaged daily mean VPD reached 1.054 kPa on August 5th that was the day with highest T_a in August 2006. 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 and August respectively.

The precipitation events have strong impact on the temporal pattern of SMI. The cumulative in situ precipitation of 34 mm in July 2006 was the lowest during the 11-year study period with the July average of 91 ± 31 mm. In contrast, the highest total precipitation in July was in 2007, reaching 146 mm. The cumulative precipitation of 48 mm in August 2006 was not as low as in July when compared to the 11-year average of 71 ± 43 mm. However, the lack of precipitation since the end of July led to the continuous drop of SMI till mid August 2006, followed by a small increase in soil moisture after a light precipitation event. The SMI increased to be above 0.2 in the end of August with a heavy precipitation event exceeding 25 mm in one day. Moreover, the precipitation in June 2006 was also less than the 11-year average (45 vs. 70 ± 24 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 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 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).

The non-linear relationship between the daytime averaged GPP and ET was also found in the JSBACH simulated result (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

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condition (SMI < 0.15) during the summer drought in 2006, the model simulated much less reduction of GPP, while the ET

360   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.

365   **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 night time and the days affected by rain (see details in section 2.2) removed also the small values of GPP and ET. Linear regressions were fitted between GPP (ET) and environmental variables for each soil moisture group to emphasize the deviating differences of dependence of GPP (ET) on environmental variables under different soil moisture conditions.

370   The regression parameters, correlation coefficient 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

375   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

380   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

385   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.

390   **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 µg C kPa /mg H$_2$O (the mean value for the days with SMI equal or larger than 0.2) to 3.93 µg C kPa /mg H$_2$O (the mean value for the days with SMI smaller than

395   0.2), and uWUE did not change under the severe soil moisture drought at Hyytiälä (Fig. 4 (a)). The simulated EWUE decreased

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less and the simulated IWUE increased more (from 3.62 µg C kPa /mg H_2O to 5.17 µg C kPa /mg H_2O) than the observation, which is mainly because of a smaller decrease of the simulated GPP 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

405 transpiration based EWUE, IWUE and uWUE (Fig. S3 in Supplementary Material) showed similar results to those three metrics calculated with ET.

4. Discussion

4.1 Drought impacts on GPP and ET

410 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 regulation of the plants, which limits plant carbon assimilation and transpiration. The decreased ET due to soil moisture drought may increase atmospheric VPD, which could in turn intensify stomatal closure (Eamus et al., 2013; Jarvis, 1976). Moreover, the GPP and

415 ET were decoupled and EWUE decreased due to the soil moisture drought. Different to EWUE, IWUE increased but uWUE showed no changes during the severe soil moisture drought at Hyytiälä. IWUE depends on the difference between ambient partial pressure of CO_2 (Ca) and a weighted average of inner leaf partial pressure of CO_2 (Ci) through the canopy within the tower footprint (Beer et al., 2009). It has been shown that the term (1-Ci/Ca) increases as VPD increases (Wong et al., 1979). Thus, the increase in IWUE during drought was a result of decreased stomatal conductance due to increased VPD. The uWUE

420 was formulated to be more independent of a varying VPD than IWUE. According to Xie et al. (2016), both IWUE and uWUE at a flux site increased and reached their maximum values over long-term during a severe drought in central and southern China in the summer of 2013. In this work, the unchanged uWUE during this drought event demonstrate that the trade-off between carbon assimilation and transpiration of the boreal Scots pine forest was not disturbed by drought at the study site, even though the stomatal conductance decreased.

425 ### 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 a response to air humidity, and therefore the stomatal conductance in JSBACH is insensitive to atmospheric VPD (Knauer et al., 2015). In

430 Knauer et al. (2015), Ball-Berry model (Ball et al., 1987) has been found to be the 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

435 be important for the 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.

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Moreover, when comparing results from the EC data and simulations, it should be kept in mind that the EC method has its 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. Nevertheless, 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. The ecosystem water use efficiency (EWUE) decreased, whereas the inherent water use efficiency (IWUE) increased and the underlying water use efficiency (uWUE) was unchanged during the severe soil moisture drought at the site. The EWUE is very sensitive to the daily changes of GPP and ET. The increase in IWUE during drought was due to the decreased stomatal conductance of plants under increased VPD. The unchanged uWUE indicates that the carbon assimilation and transpiration coupling of the boreal Scots pine forest was not disturbed by the drought event at this site, although the stomatal conductance of plants decreased.

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. The differences between the observed and the model results suggest that in order to adequately simulate effects of drought on plant functioning the combined effects of atmospheric and soil moisture drought on stomatal conductance have to be included in the stomatal conductance model in JSBACH. Moreover, inclusion of non-stomatal limitations on photosynthesis during drought, e.g., reduced mesophyll conductance or carboxylation capacity, may additionally improve the model results (Keenan et al., 2010).

This study gives a view of the response of water use efficiency to a summer drought event in a boreal Scots pine forest in

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530 Finland, and further suggests thatimproving our knowledge of ecosystem processes in land surface models are of great importance when estimating biosphere-atmosphere feedbacks of terrestrial ecosystems under climate change.

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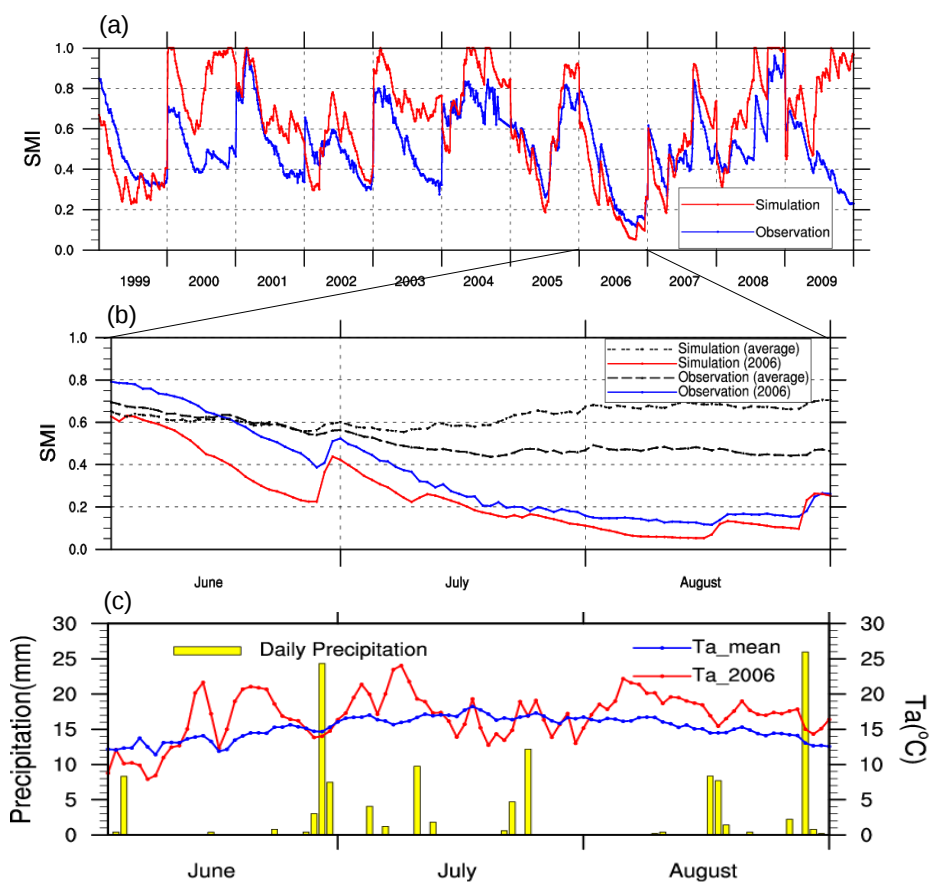
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Figure 1: (a) Daily mean soil moisture index (SMI) at Hyytiälä from observation and the JSBACH simulation for the summer months (June, July, August) in the 11-year study period (from 1999 to 2009). (b) Daily mean SMI at Hyytiälä from observation and 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.
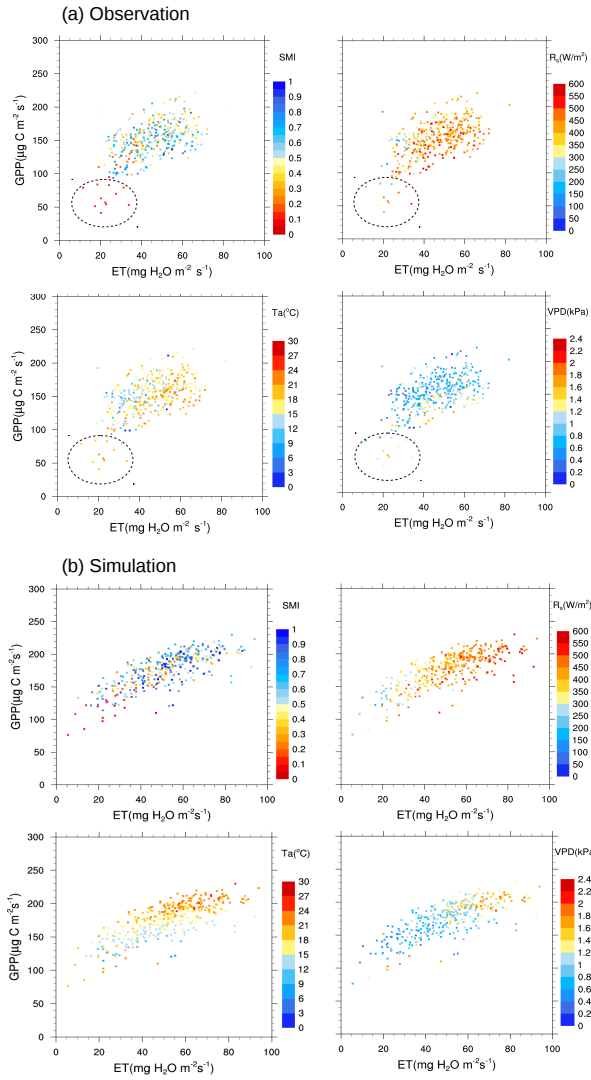
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Figure 2: Relationship between the daytime averaged gross primary production (GPP in μg C m^{-2}s^{-1}) and evapotranspiration (ET in mg H$_2$O m^{-2} s^{-1}) at Hyytiälä in the summer months (June, July, August) of the 11-year study period (from 1999 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. In the observation, the group of data under the very dry soil moisture condition showing GPP values lower than other days is marked with dashed circle.
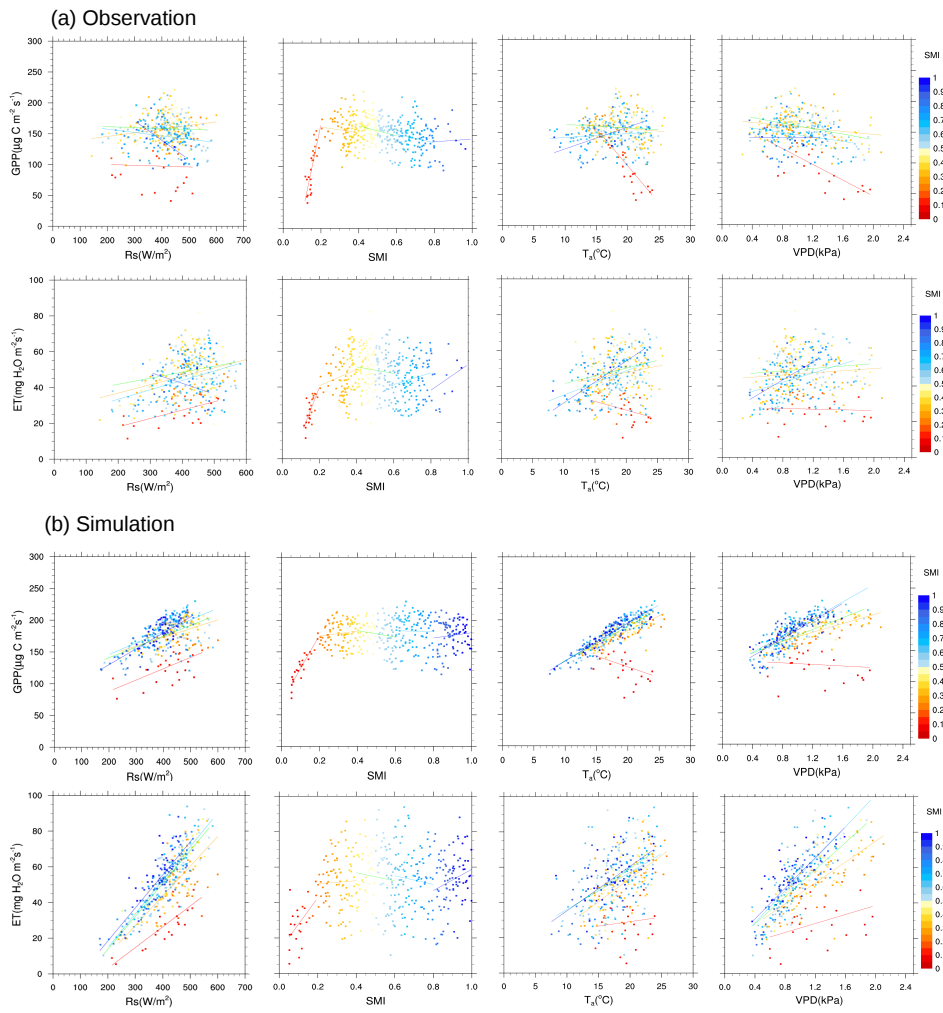
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Figure 3: Response of daytime mean gross primary production (GPP in µg C m^{-2}s^{-1}) and evapotranspiration (ET in mg H$_2$O m^{-2} s^{-1}) to daytime mean incoming shortwave radiation (R$_s$), daytime mean air temperature (T$_a$), daytime mean vapour 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).
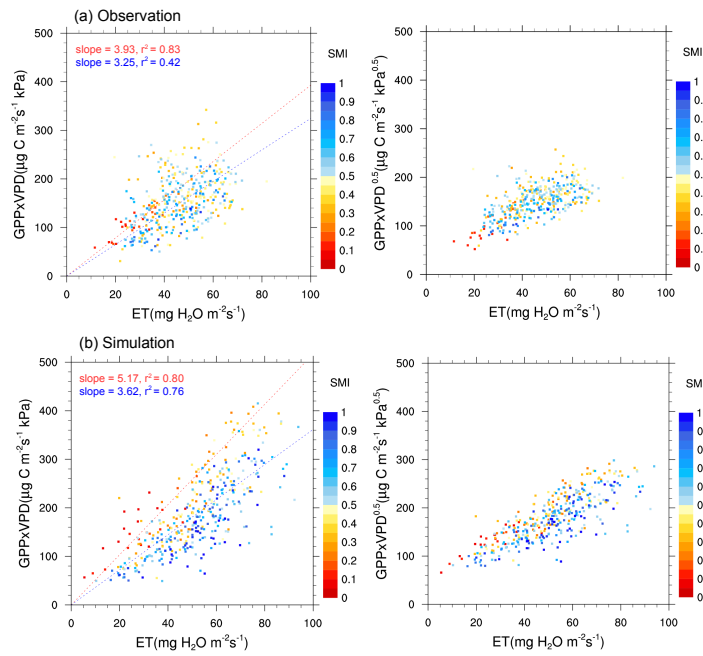
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Figure 4: The dependence of the product of daytime mean gross primary production (GPP in µg C m^{-2}s^{-1}) and daytime mean vapour pressure deficit (VPD) on evapotranspiration (ET in mg H$_2$O m^{-2} s^{-1}) (i.e., GPP×VPD/ET, which represents the inherent water use efficiency (IWUE)), and the dependence of the production of GPP and the square

740 **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**

745 **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.**

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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

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