Authors' Response to Associate Editor and Reviewers

Evaluating the Community Land Model (CLM 4.5) at a Coniferous Forest Site in Northwestern United States Using Flux and Carbon-Isotope Measurements
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We would like to thank the Associate Editor, Dr. Andreas Ibrom, and the two anonymous Reviewers for their comments, which greatly helped to improve this manuscript.

All comments are listed below in italic font and are numbered for easy reference. Our responses are in blue, regular font. The responses to Reviewers 1 and 2 are reproduced from the original document published in the discussion board, with the following modification: at the end of each response, where applicable, we indicate the changes that were implemented and their location (P[page_number]L[line number]) in the revised manuscript (blue, bold font). Cited page and line numbers in the responses correspond to our published discussion paper. The cited literature is listed at the end of this document. Figures R1–3 correspond to the new figures included in this document.

On behalf of all authors,

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Comments from Reviewer #1

This paper describes an application of the CLM model to the Wind River flux tower site.

[RC1.1] *The first point to note is that model parameterization is done in the good old-fashioned way. When applied out of the box with standard PFT parameters, the model does not fit very well. Hence, the model needs to be calibrated. This calibration is done by adjusting parameter values manually, based on the literature and some trial-and-error, until the fit to the data is not too bad. Most groups are moving away from this approach to parameterization, to a more rigorous statistical framework such as Bayesian calibration, which yields more defensible parameter values. I don't think it's essential that the authors do this, but it would be good if they could give at least some justification for sticking with the traditional method of parameterization.*

A: The adjusted parameters were primarily based on biological measurements at Wind River or at similar stands in the Pacific Northwest (Sect. 2.6, P7L5–16). Soil hydraulic parameter values were switched back to the values in CLM 4.0 (via a configuration option in the model), leading to a more accurate simulation of soil moisture at the site. Root distribution parameters were also changed in order to reduce the excessive late-summer soil moisture stress and gross primary production (GPP) down-regulation in the model. The default values for the needleleaf evergreen temperate tree PFT were replaced by the default values for broadleaf evergreen temperate tree PFT, shifting roots to deeper soil layers (this change was justified based on our physical understanding of the site – see further discussion in our response to RC1.13 and RC2.3). The SLA_0 parameter (specific leaf area at canopy top) was adjusted by manual trial and error (decreasing values were attempted), with m (linear coefficient in Eq. A1) values constrained by Eq. (A2), the SLA_0 value, and the site observations of leaf area index (LAI) and leaf carbon, aiming to minimize model errors in the simulation of GPP and LAI (Sect. A4).

A Bayesian calibration approach would be complicated by the current lack of prior parameter distributions within CLM in order to create a model ensemble and the computational expense of running a calibration. Commonly used techniques such as Markov Chain Monte Carlo (MCMC) are prohibitively expensive with long CLM simulations, and more advanced techniques for calibration (e.g. using surrogate modeling approaches) are still under development. The simpler approach we used proved to be an effective method to improve model performance at the Wind River AmeriFlux site. Given our observation-based parameter adjustments, combined with careful trial and error adjustments to match the observed surface fluxes, it is unlikely that a Bayesian approach could provide a meaningfully better fit.

Manuscript revision

Added in P10L1–7: “Bayesian parameter calibration is a common approach used in modelling studies to account for both the prior parameter distributions and more recent observations. In this case, a Bayesian calibration approach would be complicated by the current lack of prior parameter distributions within CLM in order to create a model ensemble and the computational expense of running a calibration. Commonly used techniques such as Markov Chain Monte Carlo (MCMC) are prohibitively expensive with long CLM simulations, and more advanced techniques for calibration (e.g. using surrogate modeling approaches) are still under development. The simpler approach used here proved to be an effective method to improve model performance at the Wind River AmeriFlux site.”

[RC1.2] *The second striking thing about this manuscript was the almost complete lack of reference to the literature in the Discussion. The Results and Discussion are combined into the one section – never a good idea in my view. Here, there is almost no discussion of the results, and no attempt to place the results in the context of the literature. Overall, I came away with a strong “so what” feeling: the authors do not do a good job of articulating why they want to calibrate CLM for this site, nor what we get out of it. There is little in the Introduction to motivate the study, and nothing in the conclusions about how this work advances the field in general. I very strongly suggest that the authors - Better motivate the study in the Introduction, with an expectation of the kinds of questions that this work can address - Separate the Results from the Discussion -Focus the Discussion on what we learn from this study, and ensure that it is placed in the broader context of the literature with appropriate citations.*

A: The key findings in our paper, summarized below, represent important contributions to the modeling community and are stated in the Conclusions. We intend to include suggested citations from Reviewer 2 to bolster the Introduction and more clearly lay out motivation to why work like this is important to the modeling community. We will also improve the discussion of our results in the context of the literature, especially Raczka et al. (2016) (nitrogen limitation in CLM; see response to RC2.1.2), Wharton et al. (2009) (observed physiological response to water stress at Wind River; see response to RC2.1.1), and previous studies involving the simulation of carbon isotopes with different land models, such as SiB and SiB-CASA (e.g., Randerson et al. 2002; Suits et al. 2005; Van der Velde et al. 2013,2014). We will also separate Results from Discussion, as suggested by the Reviewer.

Key points:

Here we assess the current version of the Community Land Model (CLM 4.5, Oleson et al. 2013), focusing primarily on the model skill in the simulation of stomatal conductance and its response to water stress (P3L5–8). The Wind River site was chosen for this study because of its climatology (dry summers) and long record of meteorological, biological, surface flux (energy and carbon), and carbon isotope measurements for model assessment (P4L20–22). We leveraged the inclusion of photosynthetic ^{13}C discrimination dynamics within CLM 4.5 to better diagnose the simulation of stomatal conductance at the site.

As discussed in P6L29–P7L4, our initial CLM simulations at Wind River using out-of-the-box parameters performed poorly, which is not quite a surprise given the fact that those parameters are based on global optimizations. It is also important to mention that Wind River is characterized by a unique old-growth forest, susceptible to stand age effects (Wharton et al. 2009). The default model parameters, likely based upon secondary-growth forests, may therefore not be appropriate. In this study the presentation of the results and discussion on model performance focus on the simulations using calibrated parameters. Note that, without calibration, we would not be able to properly test the new model structure, especially the photosynthetic ^{13}C discrimination scheme.

Overall, the calibrated CLM was able to simulate the observed response of canopy conductance to atmospheric VPD and soil water content, reasonably capturing the impact of water stress on ecosystem functioning (P12L29; P13L8; P13L25). The calibrated parameters we present in the paper may be of use for future modelling studies involving stands of similar age and composition under a similar climate regime (P13L30).

A critical adjustment was a significant reduction of the slope in the Ball-Berry stomatal conductance equation (m_{bb}) from 9 to 6, in alignment with observations reported in the literature for conifer trees and with the CLM results by Mao et al. (2016) for a loblolly pine stand in southeastern USA (Sect. A9). It also corroborates the recommendation of a lower m_{bb} value by Raczka et al. (2016) based on CLM runs at a subalpine conifer forest site in Colorado, USA. Currently, CLM uses the same m_{bb} value (9) for all C3 plants. Based on the results, we originally concluded that a future release of CLM would benefit from using a distinct m_{bb} value (6) for conifers (P14L1). However, additional analysis indicates that the significant reduction in m_{bb}

mostly accounted for the partial coupling between net leaf photosynthesis (A_n) and stomatal conductance (g_s) resulting from the nitrogen limitation scheme in the model. This partial coupling between A_n and g_s is a shortcoming of CLM (Raczka et al. 2016; Metcalfe et al. 2016) which we will more formally address in the revised paper (see further discussion in our response to RC2.1.2). We speculate that a lower m_{bb} value for C3 plants other than conifers would also be necessary given the current nitrogen limitation scheme in CLM. Even so, we believe that a distinct parameterization for conifers, as done in other models such as SiB, would still benefit CLM.

As discussed in P11L11–23 and P14L12–17, our results show that carbon isotope measurements can be used to constrain stomatal conductance and intrinsic water-use efficiency in CLM, as an alternative to eddy-covariance flux measurements. Our results also show that carbon isotopes expose a conceptual weakness in CLM's carbon allocation scheme (lack of an explicit representation of carbohydrate storage pools) and may guide future improvements in the model. The need for a better representation of carbohydrate storage pools within CLM is also highlighted by the $^{13}CO_2$-labeling study conducted by Mao et al. (2016) (P10L21).

The key findings discussed above represent important contributions to the modeling community and are stated in the Conclusions (the recent findings related to the nitrogen limitation scheme will be included in the revised paper).

Manuscript revision

We carefully followed the recommendation from Reviewer 1:

1. Introduction was significantly revised. Additional citations were included, helping to more clearly lay out the motivation of our study.

2. Discussion of results was expanded as explained above. A separate "Discussion" section was created (new Sect. 4), where we focus on the key findings of our study.

Abstract and Conclusion were revised accordingly.

Some comments on the methods:

[RC1.3] *The drought stress factor should be more clearly defined: I'd like to see the equation for the plant wilting factor, which apparently depends on both soil water potential (state variable) and the plant dependent response to water stress.*

A: In CLM Version 4.5, the plant wilting factor for soil layer i is defined as:

$$w_i = \begin{cases} \frac{\Psi_c - \Psi_i}{\Psi_c - \Psi_o}\left[\frac{\theta_{sat,i} - \theta_{ice,i}}{\theta_{sat,i}}\right] \le 1 & \text{for } T_i > T_f - 2 \text{ and } \theta_{liq,i} > 0 \\ 0 & \text{for } T_i \le T_f - 2 \text{ or } \theta_{liq,i} \le 0 \end{cases}$$

where Ψ_i is the soil water matric potential, Ψ_c and Ψ_o are the soil water potential when stomata are fully closed or fully open, respectively ($\Psi_c = -255000$ mm and $\Psi_o = -66000$ mm for NETT PFT), $\theta_{sat,i}$ is the saturated volumetric water content, $\theta_{ice,i}$ is the volumetric ice content, $\theta_{liq,i}$ is the volumetric liquid water content, T_i is the soil layer temperature, and $T_f = 273.15$ K is the freezing temperature of water. w_i and root fraction (r_i, Eq. A3) are used to calculate the soil moisture stress factor β_t (Eq. 3). We will include the w_i equation in the revised paper.

Manuscript revision

We added the w_i equation (Eq. 5)

[RC1.4] *I don't understand the use of the factor 'd' in equations 5 & 6. As I understand it, the relationship A = gs/1.6 (Cs – Ci) is a physical description of the diffusion process through the stomata. How can this be modified by nitrogen limitation? Or is this something that affects the "isotopic" Ci/Ca only?*

A: The method in which CLM 4.5 incorporates nitrogen down-regulation of photosynthesis complicates the implementation of the above equation. Although initially the net leaf photosynthesis (A_n) and leaf stomatal conductance (g_s) are "fully coupled", meaning A_n and g_s are solved simultaneously, this is done initially without including the effects of nitrogen limitation upon assimilation rate. Therefore, the initial fully-coupled solution between A_n and g_s is the "potential" assimilation rate that leads to a potential gross primary production ($\mathrm{GPP_{pot}}$). CLM 4.5 then down-regulates $\mathrm{GPP_{pot}}$ (and potential A_n) according to what nitrogen is available, and what nitrogen is required to allocate new carbon tissue based upon C:N ratio. This down-regulation is used to calculate actual GPP (and actual A_n). This is a weakness in CLM, because this downscaling de-couples A_n from g_s, and is why CLM 4.5 is a "partially-coupled" model.

The nitrogen photosynthetic downregulation factor in Eqs. (5) and (6) is defined as

$$d = \frac{\mathrm{CF_{avail\_alloc}} - \mathrm{CF_{alloc}}}{\mathrm{GPP_{pot}}}$$

where $\mathrm{CF_{avail\_alloc}}$ is the carbon flux from photosynthesis which is available to new growth allocation and $\mathrm{CF_{alloc}}$ is the actual carbon allocation to new growth (limited by nitrogen availability). Actual GPP is calculated as

$$\mathrm{GPP} = \mathrm{GPP_{pot}}(1 - d).$$

The net leaf photosynthesis term A_n in Eqs. (5) and (6) corresponds to potential A_n. In order to make c_i consistent with the actual, nitrogen limited GPP, A_n is multiplied by $(1 - d)$ in Eqs. (5) and (6). Note, however, that g_s in those equations is consistent with A_n, not $A_n(1 - d)$. We discuss the implications of this mismatch in our response to RC2.1.2. A more detailed description of CLM 4.5's nitrogen limitation scheme and its shortcomings is presented by Raczka et al. (2016).

We will include this information in the revised paper.

Manuscript revision

The information discussed above was included in Sect. 2.1.

[RC1.5] *I note that mesophyll conductance also affects the isotopic ratio – is this accounted for in this model?*

A: CLM 4.5 does not account for mesophyll conductance (intracellular CO_2 is assumed to be the same as intercellular CO_2). Raczka et al. (2016) hypothesizes that inclusion of mesophyll conductance could improve the magnitude of ^{13}C discrimination in the model. We will discuss this in the revised paper. Mesophyll conductance was recently incorporated and tested in CLM 4.5 (Sun et al., 2014), and in the future we could explore this by working to link mesophyll conductance to the carbon isotope submodel.

<u>Manuscript revision</u>

This is addressed in P6L13 and P21L12.

[RC1.6] *Please add a description of how the model scales from leaf to canopy. As all of the comparisons are with canopy-scale GPP, LE and Gs, it is important for the reader to know the principal assumptions underlying this scaling. How is leaf isotopic composition modeled for the whole canopy? How is leaf conductance scaled to the canopy?*

A: Leaf stomatal resistance and photosynthesis are solved separately for sunlit and shaded leaves. Canopy conductance is given by

$$G_s = \frac{1}{r_b + r_s^{sun}} \mathrm{LAI}^{sun} + \frac{1}{r_b + r_s^{sha}} \mathrm{LAI}^{sha}$$

and potential GPP by

$$\mathrm{GPP}_{\mathrm{pot}} = (A_n^{sun} + R_d^{sun})\mathrm{LAI}^{sun} + \left(A_n^{sha} + R_d^{sha}\right)\mathrm{LAI}^{sha}$$

where r_b is the leaf boundary layer resistance, r_s is the leaf stomatal resistance, LAI is the leaf area index, A_n is the net leaf photosynthesis, and R_d is leaf-level respiration (sun and sha superscripts denote sunlit and shaded leaves, respectively). Photosynthetic parameters such as V_{cmax25} are solved separately for sunlit and shaded leaves and their canopy scaling scheme is detailed in Oleson et al. (2013, Sect. 8.3). Actual GPP is calculated from $\mathrm{GPP}_{\mathrm{pot}}$ and the nitrogen photosynthetic downregulation factor, d (see our response to RC1.4). Note that, as discussed in Sect. 2.7, we opted to calculate a modeled canopy conductance using the Penman-Monteith method (Eq. 7) and modeled surface fluxes in order to allow a more direct comparison against observations (Penman-Monteith method using observed surface fluxes).

$\delta^{13}C_{GPP}$ is determined based on the carbon assimilation and photosynthetic ^{13}C discrimination by sunlit and shaded leaves and their respective leaf area indices. The carbon isotope ratio of newly allocated carbon is the same as $\delta^{13}C_{GPP}$. The δ^{13}C of the leaf carbon pool depends on the inward allocation flux and its δ^{13}C ($\delta^{13}C_{GPP}$), in addition to the turnover time of the pool.

We will incorporate these descriptions in the revised paper.

Manuscript revision

The above descriptions were added in Sect. 2.1.

[RC1.7] *The model is evaluated against gap-filled flux data. In my view that's not acceptable: evaluating a model against gap-filled data is comparing one model against another. The model should only be evaluated against non-gap-filled data.*

A: Gap-filled data (AmeriFlux L4 data) were used for a general assessment of CLM in respect to the simulation of energy and carbon fluxes (Fig. 3). For the entire period of study (1998–2006), a reasonably small fraction of the half-hourly energy flux data actually corresponds to gap-filled data (22% for the sensible heat flux data and 24% for the latent heat flux data). In our view the L4 data are sufficient for a general evaluation of seasonal patterns of CLM. Note that we did *not* use gap-filled flux data for calculations (e.g. canopy conductance) in our study, nor did we use them to calculate annual integrals of net ecosystem exchange (NEE) or gross primary production (GPP), that may be influenced by the gap-filling method.

The GPP and ecosystem respiration (ER) data, strictly speaking, do not correspond to observations but to model products based on NEE measurements at the site, as pointed out in the text (P9L5). We opted to use these products as a reference in the evaluation of CLM. Note that comparing modeled output against partitioned GPP and ER flux tower data is common in the literature.

[RC1.8] *Please describe more clearly the process used for calibration. For example, p16 says that SLA0 is optimized by aiming to minimize model errors in site observations of LAI and Cl – was this done using a solver function, or simply by manual trial and error?*

A: The adjusted parameters were primarily based on biological measurements at Wind River or at similar stands in the Pacific Northwest (Sect. 2.6, P7L5–16). Soil hydraulic parameter values were switched back to the values in CLM 4.0 (via a configuration option in the model), leading to a more accurate simulation of soil moisture at the site. Root distribution parameters were also changed in order to reduce the excessive late-summer soil moisture stress and gross primary production (GPP) down-regulation in the model. The default values for the needleleaf evergreen temperate tree PFT were replaced by the default values for broadleaf evergreen temperate tree PFT, shifting roots to deeper soil layers (this change was justified based on our physical understanding of the site – see further discussion in our response to RC1.13 and RC2.3). The SLA_0 parameter (specific leaf area at canopy top) was adjusted by manual trial and error (decreasing values were attempted), with m (linear coefficient in Eq. A1) values constrained by Eq. (A2), the SLA_0 value, and the site observations of leaf area index (LAI) and leaf carbon, aiming to minimize model errors in the simulation of GPP and LAI (Sect. A4). We will clarify in the revised text that SLA_0 was adjusted by manual trial and error.

Manuscript revision

Clarification that SLA_0 was adjusted by manual trial and error was added in P24L4.

On the results:

[RC1.9] *Figure 2 could show observations as well as model output, making it easier to visualize the model-data correspondence. Please indicate in Table 2 what the errors refer to (+/-SE? 95% CI? Range?)*

A: We will add the observations from Table 2 in Fig. 2 as suggested. In Table 2, the observations from the AmeriFlux database are given as *mean* ± *standard deviation*. The values from Fessenden and Ehleringer (2003) correspond to the range of observed values in their Figs. 2b (δ^{13}C leaf) and 3 (δ^{13}C SOM). We will clarify this in Table 2.

Manuscript revision

We added the observations from the original Table 2 in Fig. 2 and removed Table 2 from the revised manuscript. Observed $\delta^{13}C_{leaf}$ and $\delta^{13}C_{SOM}$ are now expressed as avg ± std. dev. instead of range. Information about the error bars is included in the figure caption.

[RC1.10] *I was unsure how to evaluate the leaf isotopic data. Are the modeled values to be compared with the top, bottom, or average of the canopy? See note above about how isotope discrimination is scaled to the whole canopy.*

A: CLM is a two-big-leaf (sunlit and shaded leaves), single-canopy-layer model (a multi-layer option is available, but not supported). The modeled leaf δ^{13}C output corresponds to the isotopic signature of the entire leaf carbon pool, which is calculated from both sunlit and shaded portions of the leaf canopy. Further details are provided in our response to RC1.6.

The observed leaf δ^{13}C values in Table 2 correspond to measurements at canopy top (55 m), middle (25 m), and bottom (2 m). As pointed out by Fessenden and Ehleringer (2003), the decrease in the leaf δ^{13}C values (i.e., increase in photosynthetic ^{13}C discrimination) with canopy depth can be explained by light reduction within the canopy. The observed mid-canopy values are expected to better represent the isotopic composition of leaves for the whole canopy, in comparison with the observed values at the two canopy extremes, especially given the larger amount of leaf biomass in mid canopy. Therefore, the mid-canopy leaf δ^{13}C values in Table 2 should provide a better reference for evaluating CLM, which does not explicitly resolve the leaf δ^{13}C by canopy height. We will discuss this in the revised paper.

Manuscript revision

We added the above discussion in the revised paper (P11L22–P12L2), with a few modifications:

"It is important to clarify that CLM has leaf properties that vary continuously with canopy depth, and that two leaf categories (sunlit and shaded leaves) are estimated dynamically on every time step, as a function of canopy structure and solar elevation angle (Thornton and Zimmerman, 2007). The modeled leaf δ^{13}C output corresponds to the isotopic signature of the entire leaf carbon pool, which is calculated from both sunlit and shaded portions of the leaf canopy (see Sect. 2.1). The observed leaf δ^{13}C values in Fig. 2g correspond to measurements at canopy top

(55 m), middle (25 m), and bottom (2 m). As pointed out by Fessenden and Ehleringer (2003), the decrease in the observed leaf δ^{13}C values (i.e., increase in photosynthetic ^{13}C discrimination) with canopy depth can be explained by light reduction within the canopy. In principle, the observed mid-canopy values are expected to better represent the isotopic composition of leaves for the whole canopy, in comparison with the observed values at the two canopy extremes, especially given the larger amount of leaf biomass in mid canopy. However, considering how light is reduced within the canopy, the top-canopy δ^{13}C value should still be representative of a significant fraction of the canopy as well, so the whole canopy δ^{13}C is expected to lay somewhere in between the top- and mid-canopy values. As shown in Fig. 2g, the modeled δ^{13}C of the leaf carbon pool was the average between the observed values at canopy top and middle."

[RC1.11] *It would have been good to see the model performance with the parameters out of the box, as well as model performance with calibrated parameters, in order to visualize the effect of altering model parameters.*

A: Figures R1 and R2 below compare the performance of CLM for key model outputs when using "out-of-the-box" parameters and calibrated parameters. We intend to add these figures in the Appendix of the revised paper. Note that the model performance improved substantially after calibration and allowed for a fair test of the photosynthetic ^{13}C discrimination scheme in CLM.

Manuscript revision

Figures R1 and R2 were added in the revised manuscript (Figs. A4 and A5, respectively).

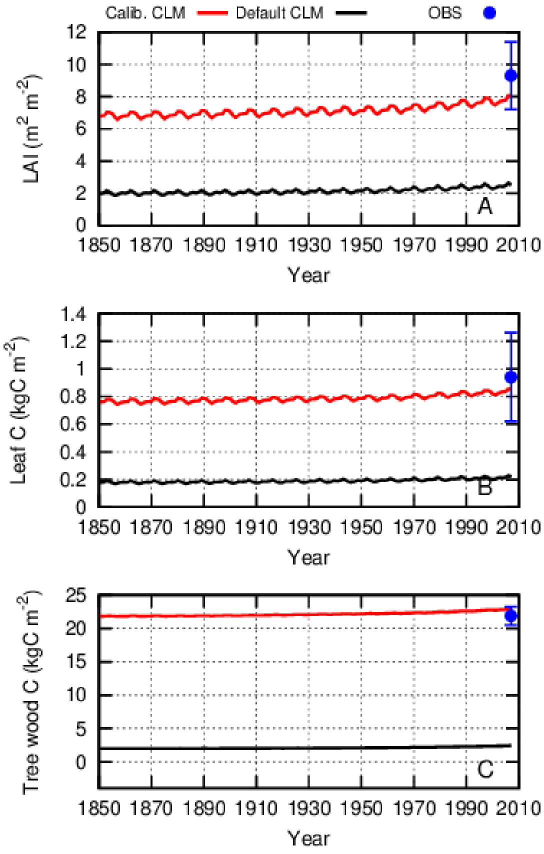

Figure R1. Comparison of CLM performance at Wind River when using default, "out-of-the-box" parameters (black lines) and calibrated parameters (red lines). Observations (*mean* ± *std. dev.*, blue points and error bars) are from the AmeriFlux database.

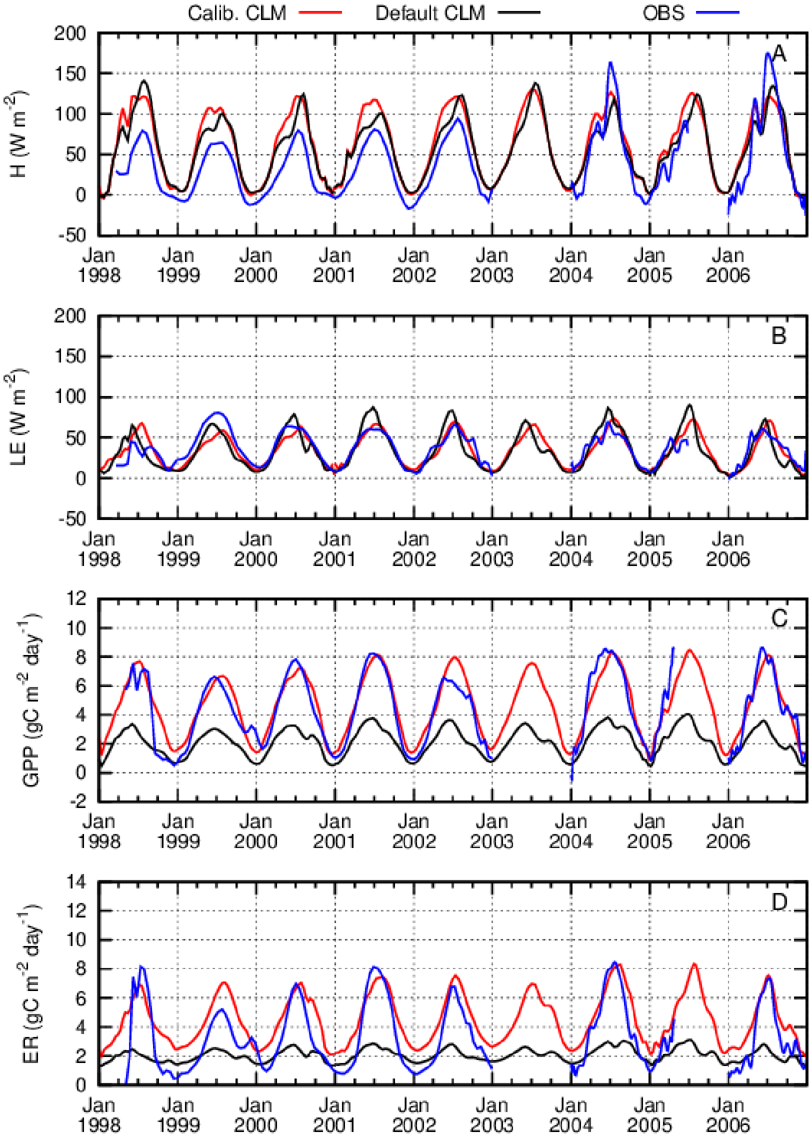

Figure R2. Comparison of CLM performance at Wind River when using default, “out-of-the-box” parameters (black lines) and calibrated parameters (red lines) against site observations (blue lines). For clearer visualization, the data presented correspond to Bézier-smoothed daily averages as in Fig. 3.

[RC1.12] *Please discuss the lack of energy balance closure at this site. The model assumes the energy balance is closed; if the data show a lack of closure the model must show a bias in its predictions of either LE or H. How large is the lack of closure at this site, and how does it affect the model comparison to data?*

A: We calculated the energy balance ratio, $\mathrm{EBR} = (H + LE)/(R_n - G)$, using 30-min, L2 (V007) data from the AmeriFlux repository (H is sensible heat flux, LE is latent heat flux, R_n is net radiation, and G is soil heat flux). We used data from June–September, 10:00–14:00, and rejected periods with rain or unfavorable wind direction. With the available data, we were able to calculate EBR for the years of 1998–2001, 2004, and 2006.

The overall mean EBR is 0.88. The energy balance closure for years 2004 and 2006 is high (mean $\mathrm{EBR} = 1.01$ and 1.09, respectively). Note in Fig. 3a and b that the model bias in the estimation of H and LE is reduced in those years. In years 1998, 2000 and 2001, mean EBR is significantly lower (0.63, 0.69 and 0.76, respectively). Note in Fig. 3a the positive bias in modeled H for those years. As discussed in the text (P9L13), the observed H values in 1998–2003 are significantly smaller than in 2004–2006, while the LE observations show approximately the same pattern over the years. The change in the pattern of observed H was reported as a potential data issue in the Wind River site documentation (AmeriFlux repository[#]). The low EBR for years 1998, 2000 and 2001 supports this notion, and suggests that the observed H values were too low in 1998–2003. Mean EBR in 1999 is relatively high (0.92), where the reduced H values (Fig. 3a) are compensated by larger LE values (Fig. 3b). In that year, modeled H (LE) has a positive (negative) bias in respect to the observations.

[#] ftp://cdiac.ornl.gov/pub/ameriflux/data/Level4/Sites_ByName/Wind_River_Field_Station/history_changes.txt

Manuscript revision

We included the above results in the revised manuscript (P12L22–31). The methodology used in the calculation of EBR was included in P8L3–7.

[RC1.13] *What is the average rooting depth? The SWC data shown are only to 30 cm – how much deeper than this do the roots penetrate? Is the lack of response to low SWC a function of only considering the very top soil?*

A: Shaw et al. (2004) provides a good description of rooting depth at Wind River: "Plant roots are concentrated above 50 cm in soil profiles; however, roots as deep as 2.05 m have been observed in younger forests growing on nearly identical soils (T. Hinckley personal communication). Many coarse roots of Douglas-fir extend to depths greater than 1.0 m. Tip-up mounds of windthrown western hemlock trees typically have a classic flat root plate indicative of shallow rooting" (Douglas-fir and western hemlock are the dominant species at the site).

In CLM, root fraction as a function of soil depth is calculated using Eq. (A3). With the default root distribution parameters, the total root fraction in the top 46 and 130 cm of soil is 78% and 96%, respectively (note the small fraction of roots at depths below 1.3 m (4%)). The above site description (Shaw et al. 2004) suggests that the default parameters are inadequate at Wind River, resulting in a "too-shallow" rooting profile. As discussed in Sect. A8, we adjusted the r_b root distribution parameter from 2 m^{-1} to 1 m^{-1} (based on the default CLM value for broadleaf evergreen temperate tree PFT), shifting roots to deeper soil layers, aiming to reduce the excessive late-summer soil moisture stress and downregulation of gross primary production (GPP) in the model. With the adjusted r_b parameter, the total root fraction in the top 46 and 130 cm of soil is 67% and 86%, respectively (14% below 1.3 m), which seems more reasonable based on Shaw et al.

(2004) and the fact that Douglas-fir trees at the site are about 500 years old and 40–65-m tall. Our adjustment of soil moisture stress in CLM via root distribution is therefore physically justified. This adjustment is further discussed in our response to RC1.14.

With regards to the third question, we believe the reviewer is referring to the apparent lack of response of the observed canopy conductance (G_c) to observed soil water content (SWC) (Fig. 7a). As we point out in the text (see Sect. 3.4, second and fourth paragraphs), this is likely associated with a negative bias in the observed SWC data in 1999–2002 due to a different instrumentation setup. Excluding this period in which the SWC data may be biased, CLM was able to match the observed SWC values reasonably well, especially during the summer months (note that observed precipitation was used to drive CLM). In Fig. 7b, note that the data points (G_c vs. VPD) correspond to *observations*, but those are binned according to *modeled* SWC. The impact of soil moisture on the observed G_c then becomes evident. The result supports the suspicion of a negative bias in the observed SWC data in 1999–2002.

Manuscript revision

The above discussion on root distribution at Wind River was added in the revised manuscript (Appendix A8).

[RC1.14] *The demonstration that the model over-estimates the effect of low SWC in the topsoil is interesting, but difficult to interpret without the rooting depth and the formulation for soil moisture stress being given. Nothing is said about how the model might be improved based on this observation – it would be good if the authors could identify the root cause for this mismatch and suggest how it could be addressed.*

A: See our response to RC1.13. Note that the result in Fig. 7a is likely impacted by a negative bias in the observed soil water content (SWC) data from 1999 to 2002. Please compare Fig. 7b with Fig. 8b, the former showing observed canopy conductance (G_c) on the y axis and the latter showing modeled G_c. Both figures show observed vapor pressure deficit (VPD) on the x axis and use modeled SWC (0–27cm) values to segregate the data points into different SWC regimes. The linear regression between $\log G_c$ and VPD considering all data points (regardless of SWC value) are virtually identical in both figures. When considering only data points within the lowest SWC bin, the linear regression is similar in both figures, with CLM apparently presenting a small *underestimation* of the effect of low SWC on G_c (i.e., small overestimation of G_c). It is important to point out, however, that modeled SWC was used to segregate the observations in Fig. 7b, due to the suspicion of a negative bias in part of the SWC observations, as discussed above. Overall, the results indicate that the calibrated CLM was able to reasonably simulate the observed response of canopy conductance to VPD and SWC.

Note that CLM's soil moisture stress factor, β_t, is defined in Eq. 3. It is a function of root fraction, r_i, and a plant wilting factor, w_i. The former is defined in Eq. (A3), and the latter has been included in this document (see response to RC1.3). Without any adjustments in the model, soil moisture stress was excessive, resulting in an unrealistic down-regulation of gross primary production (GPP) during late summer. The excessive soil moisture stress was especially due to an inaccurate simulation of soil moisture at the site (strong dry bias). In addition to the adjustment of soil hydraulic parameters (resolving the soil moisture issue), we also adjusted r_i, shifting roots to deeper soil layers (a physically justified approach – see further discussion in our response to RC1.13). We did not adjust w_i, but this could be a supplementary approach to better simulate β_t. This is discussed in our response to RC2.3.

[RC1.15] *Finally, a very important point, something that needs to be said: why on earth is CLM still using the Ball-Berry stomatal model? The Ball-Berry model is physiologically incorrect (see Aphalo & Jarvis 1991, and pretty much every stomatal physiology paper since). It is consistently outperformed by models based on VPD. It will incorrectly predict stomatal behaviour in future climates, when VPD is predicted to change but RH stay the same (see Sato et al. 2015 JGR). It is quite odd to read here the justification that "such improvement is expected to be small". I think it is well past time that CLM moved on from the Ball-Berry model.*

A: The CLM development team is in a better position to justify the use of the Ball-Berry stomatal model, but it is important to highlight here that the Ball-Berry model is also used in many other major land surface models (LSMs) (Sato et al. 2015; see their Appendix S3). The Ball-Berry model (based on RH) is simpler than the Leuning model (based on VPD), involving a smaller number of parameters. Note that major LSMs are designed to work in a variety of situations where simplicity of formulation can actually be a strength. The LSM intercomparison in the NACP site-level interim synthesis study by Schaefer et al. (2012), for instance, does not support the suggestion that the Ball-Berry approach is clearly inferior. The Reviewer offers Sato et al. (2015) as an example of why the Leuning model would be preferred, however, this is given in context with future climates in which the trend of RH deviates from VPD. Note that this is not the case of our study (we are hindcasting from prescribed meteorology).

In P12L25–29, we wrote: "The correlation between modeled G_c and RH was found to be slightly higher than between modeled G_c and VPD, while observed G_c correlated slightly better with VPD than RH (results not shown). The results indicate that a direct dependence on leaf VPD in CLM's stomatal conductance model, rather than leaf RH, would lead to a more accurate representation of stomatal functioning at Wind River, but overall, such improvement is expected to be small. The general dependence of modeled canopy conductance on VPD was very similar in comparison with observations, as indicated by the linear regression curve between $\log G_c$ and VPD in Fig. 8 using all data points ($\log G_c = -0.59\mathrm{VPD} + 6.04$; compare with $\log G_c = -0.59\mathrm{VPD} + 6.06$ in Fig. 7b)."

Note that our conclusions regarding the potential improvement in the simulations by having a direct dependence on leaf VPD, rather than leaf RH, in CLM's stomatal conductance model refer to the results presented in our study only.

As the Reviewer points out, in the case of model predictions under different climate scenarios, in which atmospheric VPD is predicted to change while RH stays the same, a direct dependence on leaf VPD in the stomatal conductance model becomes critical. This is a point that hopefully will be addressed in a future release of CLM, and would be more relevant for climate change simulation (our analysis uses a stable climate and is a hindcast). We intend to add this remark in the revised paper.

Manuscript revision

We added this discussion in the revised manuscript (P18L21–29): "As pointed out in Sect. 3.4, the results of the present study indicate that a direct dependence on leaf VPD in CLM's stomatal conductance model, rather than leaf RH, would lead to a more accurate representation of stomatal functioning at Wind River, but overall, for the period analyzed in the present study, such improvement is expected to be small. It is important to emphasize that this expectation refers to the results presented here only. In case of model predictions under future climate scenarios, in which atmospheric VPD is predicted to change while RH stays the same (as discussed in Sato et al., 2015), a direct dependence on leaf VPD in the stomatal conductance model becomes critical. The next CLM release (Version 5) is expected to replace the Ball-Berry model with the Medlyn model (Medlyn et al., 2011), which directly depends on leaf VPD. This modification is expected to be more relevant for climate change simulations. Note that the present analysis is based on a hindcast simulation using a stable climate."

[RC1.16] *Very finally, debating whether to mention this or not, but: I was also struck by the extreme gender imbalance of the authorship list. Ten male authors! I hope and trust that the PIs here are actively taking steps to address this imbalance in their group of collaborators.*

A: We share the Reviewer's concerns about diversity in science. We are indeed actively engaged in recruiting, mentoring, and collaborating with female scientists at all career stages.

Comments from Reviewer #2

[RC2.1] *This manuscript (MS) presented a difficult review. After the first couple of readings, I found the paper easy to read, with no obvious shortcomings. This should have prompted a favorable review, right? However, the MS does read somewhat like 'we ran a model, here is what happened' which is bothersome to me. The use of isotopes in a model is no longer novel; you need to go beyond just saying you put isotopes in a model and ran it, and say something about how this capability and our inclusion of it in models informs our understanding of natural systems. With more careful reading, more issues emerged for me.*

A: We agree that the use of isotopes in a land model is not novel, but we would like to clarify that the simulation of ^{13}C isotopes is a new feature in *CLM*. This implementation was made available in the latest release of the model (CLM 4.5) and is evaluated in our paper. Our results show that, thanks to this implementation, carbon isotope measurements can be used to constrain stomatal conductance and intrinsic water-use efficiency in CLM, as an alternative to eddy-covariance flux measurements. Our results also show that carbon isotopes expose a conceptual weakness in CLM's carbon allocation scheme (lack of an explicit representation of carbohydrate storage pools) and may guide future improvements in the model. In the revised paper, we plan to further discuss these results in the context of other land models.

Manuscript revision

The Introduction Section was substantially revised and now includes a better overview of previous modelling studies using carbon isotopes (particular attention was given to studies using ^{13}C observations as a constraint to modeled stomatal conductance). The discussion of results was expanded and better placed in the context of the literature. Following the recommendation of Reviewer 1 ([RC1.2]), we created a separate Discussion Section (Sect. 4) where we focus on the key findings of our study.

1. [RC2.1.1] *The first paragraph talks about drought, and drought stress is mentioned throughout the MS. However, drought is an anomalous reduction in precipitation from climatological values. If, climatologically, 5% of annual precipitation occurs in JJA, then a dry summer is just…normal. Drought in this part of the country will likely manifest under climate change as a longer growing season and higher summertime temperatures and VPD when compared to the present---day. If meteorological forcing from the period 1998--- 2006 is cycled multiple times to simulate the period 1850---present, you're not going to capture any slow secular changes. Really, what's being done here is an evaluation of CLM's ability to capture a mean seasonal cycle that includes a dry summer. This site has a 50+ meter tall canopy, and fluxes (LE/H) are in phase with Boreal summer. LE fluxes appear to peak in June or July, and H peaks one month or so later, from a quick inspection of Figure 3. That suggests an ecosystem that may experience some stress in late summer, but is not water---limited on the whole. Costa et al. (2010) and da Rocha et al. (2009) discuss the notion of environmental and physiological stress, albeit in Amazonian forests. At Wind River, I suspect an ecosystem that is environmentally---limited for large parts of the year (winter, obviously) and may experience some physiological stress in late summer. There may be some value in studying interannual variability (IAV), as observed GPP in 2002 (a known western drought that year) and 2006 both taper off rather quickly following an early peak. CLM does not capture this behavior in 2002, but does in 2006. But the authors do not discuss IAV, but rather concentrate on the idea of annual drought stress. I'm not buying it; you're not going to have a 50---meter canopy in a region that is water stressed. Furthermore,* βt *drops below 1 in less than half of the years, and then only to a minimum of 0.6. That's not a whole lot of stress. I strenuously object to the use of the word drought for a dry summer that occurs every year.*

   A: We thank the Reviewer in alerting us to the potential confusion between "drought stress", "meteorological drought", and "water stress" our original text may have caused. In the paper, we evaluate the capability of CLM to model the ecosystem response to seasonal water stress associated with changes in vapor pressure deficit (VPD) and soil water content (SWC). The old-growth forest at Wind River is subject to water stress each summer, which is accentuated during periods of meteorological drought (precipitation below climatological normal).

The expressions “drought stress” and “water stress” are often used interchangeably in the literature. For example, the expression “seasonal drought stress” appears often in plant physiology studies carried out at sites with Mediterranean climate (also found at Wind River) (e.g., Mooney 1987; Kurpius et al. 2003; Niinemets and Keenan 2014). At Wind River, Wharton et al. (2009) investigated the ecophysiological responses of forest stands of contrasting age to “seasonal drought”. In order to avoid confusion with meteorological drought (precipitation below climatological normal), we will use the expression “water stress” in the revised paper.

The major reason for the summer water stress at Wind River is the elevated VPD. Canopy conductance values at the site strongly decrease at moderate VPD levels, regardless of soil moisture conditions. This is shown in our paper and is more extensively discussed in Wharton et al. (2009). As pointed out in their study, “Even under moderate VPD levels, foliage at the tops of tall evergreen conifer trees often reach near critical values for cavitation due to a long path distance between the water table and the hydraulic capacity of the xylem, and as a result shut their stomata frequently (Ryan and Yoder 1997)”.

Soil moisture depletion is usually not limiting at the site because the mature trees are capable to tap water from deeper soil layers (Wharton et al. 2009). Our simulation results align with this observation, as the β_t values were equal to 1 (no soil moisture stress) throughout most of the period of study (Fig. 6; note that we adjusted the root distribution in CLM – see our response to RC1.13). However, our results show that more severe SWC depletions can impose a reasonable limitation to canopy conductance under low VPD conditions (Fig. 7b). We will further discuss these points in the revised paper.

After a careful review we found that the words “drought stress” were used ambiguously in the text, in some instances meaning water stress in the broader sense (i.e., due to decreased SWC *and* increased VPD), and in some stances meaning soil moisture stress in particular. We will revise the text to improve clarity. Most importantly, we will change the title of Sect. 3.4 from “Ecosystem Drought Response” to “Ecosystem Response to Water Stress”, and inside that section, we will change “drought stress” to “soil moisture stress”. We will also expand the discussion on VPD-related water stress.

As pointed out by the Reviewer, we cycled meteorological forcing data from 1998 to 2006 in our transient simulation (1850–2006), so the impact of any slow secular changes in the forcing data (especially in precipitation, incident short(long)wave radiation, air temperature and relative humidity) was not captured in our simulation. We will mention this limitation in the revised paper. However, it is important to note that we did use 1850–2006 transient data for atmospheric CO_2, $\delta^{13}CO_2$, and nitrogen deposition.

As discussed above, we indeed focused on evaluating CLM's capability to capture the observed mean seasonal cycle of energy and carbon fluxes, marked by seasonal water stress periods during summer. Despite our focus being on the general performance of the model (across all study years), we intend to add discussion on inter-annual variability in the revised paper, as suggested by the Reviewer.

Manuscript revision

We implemented all the changes proposed above:

1. Consistency in water stress terminology throughout the text: the expression 'drought stress' is now avoided; 'Water stress' is used in the context of VPD and SWC control on stomatal conductance; 'soil moisture stress' is used in the context of SWC control on stomatal conductance.

2. Further discussion on canopy conductance dependency on VPD and SWC at Wind River (observed and modeled results): included in Sect. 4.1.

3. Discussion on inter-annual variability: included in Sect. 3.4, P15L9–18.

2. [RC2.1.2] *As I think more and more about the paper, the notion of equifinality (multiple solutions in parameter or process space that result in a single model outcome) keeps arising. A strength of CLM is that there is a large community of researchers banging on the model, and just about any process that one can imagine is included in the model and can be turned on or off (sunlit and shaded leaves; explicit nutrient cycles; hydraulic redistribution; multiple hydrology schemes; diagnostic canopy vs. DGVM; etc., etc.). This is also a CLM weakness. There are so many knobs to turn, how can you really be sure you are turning the right ones? With this in mind, I returned to Raczka et al. (2016, hereafter R16), which simulated Niwot Ridge (NR1, another site with similar vegetation type, but dissimilar climate). Since Raczka is the second author on this MS, and Duarte is the second author on R16, these papers offer an opportunity to present a body of work that compares and contrasts CLM behavior at two sites that have a similar dominant PFT but dissimilar climate (and soil, I presume). Imagine my surprise when I find that R16 claims that the nitrogen limitation scheme is a critical component, but is not considered in sensitivity tests in this MS! R16 is happy using CLM4.5 hydrology, while the current MS states that CLM4.0 hydrology was necessary to capture realistic behavior. I was encouraged to see that both papers suggest a change from standard BB C3 slope of 9 to 6 in the evergreen needleleaf PFT, and to see that both papers see excessive discrimination of ^{13}C. But I think there is an opportunity being missed here, to compare and contrast the results at two similar---but---not---identical sites. This is an opportunity to say something about how evergreen needleleaf forests behave, as informed by dissimilar CLM simulations. The first 2 authors are at the same institution, if not in the same department, and they need to be talking to each other. I think closer coordination/comparison/contrast of the results presented in R16 and here is required. Currently, I find myself more confused than anything. Can we trust CLM at all in evergreen needleleaf forest without extensive tuning from site---specific observations?*

A: We agree with the Reviewer that the modeling community should make an effort to understand how applicable a parameterization at a single site is to other sites or regions. Although Niwot Ridge and Wind River fall into the same PFT category (needleleaf evergreen temperate tree) there are many local, atmospheric, topographical and physiological differences between the sites that put them at opposite sides of the PFT spectrum. These include differences in age: Wind River is an old growth forest (~500 years old), and it has been shown that stand age effects (Wharton et al. 2009) can lead to a higher sensitivity to environmental conditions (stomatal response), whereas Niwot Ridge is a much younger, secondary growth forest, not subject to same effects. The site soil characteristics are also much different with a deeper soil layer (>1 m) at Wind River, allowing for deep penetration of roots, whereas Niwot Ridge has generally a shallow soil layer and root structure (< 1 m). Niwot Ridge is highly dependent on spring snowmelt for photosynthesis, and is completely dormant during the winter, whereas Wind River is in a milder climate, photosynthesizing during most times of the year and relying on deep root structure for soil moisture in the dry season.

The default parameters used in CLM are optimized for global simulations, so model performance at particular sites is expected to vary greatly, requiring site-specific calibration in order to adequately simulate the observed energy and carbon dynamics. This is demonstrated in the simulations at Wind River and Niwot Ridge. Soil hydraulic parameters from CLM 4.5, in particular, were found to perform well at Niwot Ridge (simulated and observed soil moisture gave reasonable agreement) and did not require adjustments. On the other hand, these parameters were found to be problematic at Wind River (soil moisture was much lower than observations, leading to excessive late-summer water stress and down-regulation of gross primary production), requiring adjustments (soil hydraulic parameters from CLM 4.0 brought soil moisture values in general agreement with observations).

We agree with the reviewer that a closer coordination of the results presented in Rackza et al. (2016) and here is needed, especially in the context of nitrogen limitation. We intend to add the following discussion in the revised paper.

Nitrogen limitation

As discussed in our response to RC1.4, CLM calculates potential GPP ($\mathrm{GPP_{pot}}$) based on potential net leaf photosynthesis (potential A_n), which is not restricted by nitrogen availability. Leaf stomatal conductance, g_s, is calculated based on potential A_n (Eq. 2):

$$g_s = m_{bb} \frac{A_n(\beta_t)}{c_s/P_{atm}} h_s + b_{bb}\beta_t$$

After the calculation of potential A_n and g_s (and $\mathrm{GPP_{pot}}$), actual GPP is obtained by down-regulating $\mathrm{GPP_{pot}}$ based on nitrogen availability (i.e., $\mathrm{GPP} = \mathrm{GPP_{pot}}(1-d)$; see response to RC1.4). This down-regulation occurs in a decoupled fashion within the model, as the change in $\mathrm{GPP_{pot}}$ (potential A_n) does not feedback into the calculation of g_s, i.e., stomatal conductance is consistent with the *potential* net leaf photosynthesis rather than the actual, nitrogen-limited net leaf photosynthesis. This makes CLM-CN a partially-coupled model in regards to A_n and g_s (Raczka et al. 2016).

As discussed in Raczka et al. (2016), the partial coupling between A_n and $g_s$causes issues in the calculation of photosynthetic ^{13}C discrimination in CLM (Eqs. 4 and 5 in Duarte et al.). Note that in CLM's c_i/c_a equation (Eq. 5),

$$\frac{c_i}{c_a} = 1 - \frac{A_n(1-d)}{c_a}\left[\frac{1.4}{g_b} + \frac{1.6}{g_s}\right],$$

A_n (potential value) is down-regulated by the $(1-d)$ factor in order to make c_i consistent with the actual, nitrogen limited GPP. However, g_s is overestimated as it is consistent with potential A_n. When using this default nitrogen limitation scheme, the modeled ^{13}C discrimination values reported by Raczka et al. (2016) for the Niwot Ridge site were significantly overestimated, i.e., δ^{13}C values of GPP and biomass significantly smaller than observations. To improve the simulation, Raczka et al. (2016)'s approach was to remove the posteriori nitrogen down-regulation of potential A_n and $\mathrm{GPP_{pot}}$ $(d = 0)$ and include a nitrogen-limiting factor directly in CLM's V_{cmax25} equation, making the model fully coupled in respect to A_n and g_s. With this configuration, their simulation of ^{13}C discrimination improved significantly, but the values still presented a small overestimation in respect to the site observations. According to Raczka et al. (2016), an overestimation of g_s due to inadequate parameter values in the Ball-Berry equation (e.g., too large slope value) could be a reason for the mismatch.

Here, we adopted a different approach. We used the default nitrogen limitation scheme in CLM, but also calibrated g_s (via parameters m_{bb} and b_{bb} in Eq. 2) based on latent heat flux (LE) observations at the site. Mostly important, we found that a significant reduction of m_{bb} from 9 (default) to 6 was necessary. This reduction, however, must also have compensated for the potential A_n value used in Eq. 2.

In our simulation, we found an average nitrogen downregulation peak of $d = 0.25$ during late spring $(\mathrm{GPP/GPP_{pot}} = (1-d) = 0.75)$. The first term on the r.h.s. of Eq. 2, with the calibration of m_{bb}, is equal to $6A_n$. We could interpret this term as $8(0.75A_n)$, where 8 is the value of m_{bb} and $0.75A_n$ is an approximation of the actual net leaf photosynthesis.

Even though A_n and g_s were not fully coupled in our simulation, by calibrating g_s we were able to significantly reduce the mismatch between actual photosynthesis and stomatal conductance and satisfactorily simulate the observed GPP, LE, and δ^{13}C values (leaf, SOM) at the site. We expect a fully coupled simulation using a nitrogen limitation downscaling factor of 0.75 directly in the V_{cmax25} equation and $m_{bb} = 8$ to lead to similar results. The downscaling factor is consistent with the value reported by Oleson et al. (2008) (0.72; Appendix G and Table G1 in their paper) for the needleleaf evergreen temperate tree PFT in CLM. The m_{bb} parameter value (8) is smaller than the default in CLM (9).

When using the default nitrogen limitation scheme in CLM, a stronger reduction of m_{bb}, from 9 to 6, was necessary to simulate the carbon and energy dynamics at Wind River. This aligns with the results by Mao et al. (2016) for a loblolly pine stand in southeastern U.S. They were able to simulate the site dynamics, including biomass δ^{13}C values, with an optimized m_{bb} of 5.6. As discussed in Appendix A9, CLM uses a default m_{bb} value of 9 for all C3 plants, while the experimental literature indicates reasonably lower values for conifers. However, as discussed above, our results indicate that the significant reduction of m_{bb} from 9 to 6 was mostly necessary to compensate for the potential A_n value used in Eq. 2. The default m_{bb} value of 9 seems more adequate for fully coupled simulations using the V_{cmax25} downscaling approach.

In summary, our results indicate that it is possible to account for partial coupling in CLM through the adjustment of stomatal slope to achieve reasonable carbon and energy exchange behavior (including ^{13}C discrimination). This is also supported by the results in Mao et al. (2016). The caveat of this approach is that m_{bb} is adjusted beyond its intended range, compensating for structural error within the model. Overall, this approach is expected to lead to similar results in comparison with the V_{cmax25} down-regulation/m_{bb} calibration approach (fully-coupled CLM), but is still not a perfect solution for the partial coupling issue. The approach we used is sufficient for the purpose of our study, but we intend to run an additional simulation in “fully-coupled mode” to provide results for comparison in the revised paper.

The shortcomings of the current nitrogen limitation scheme in CLM are also discussed in Metcalfe et al. (2016). They propose a new scheme in which GPP is not down-regulated and the excess photosynthate is allocated to a new nonstructural carbohydrate storage pool within the model. Testing ^{13}C discrimination with this new scheme is something we recommend for future studies.

Manuscript revision

We now clearly address the nitrogen limitation issue in the revised manuscript, incorporating the above discussion in the text. Changes can be observed throughout the manuscript, especially in these Sections: Introduction; Methodology/Model Description (Sect. 2.1); Discussion/Calibration of CLM (Sect. 4.2); Discussion/Recommendations for Structural Improvement within CLM (Sect. 4.3); Appendix A9 (calibration of stomatal conductance).

Note: we tested the alternative nitrogen limitation scheme (V_{cmax25} downscaling; Raczka et al., 2016) at Wind River and were able to verify the tradeoff between adjustment of stomatal slope and changes to the nitrogen limitation scheme, discussed above. However, the hypothesis that using $0.75V_{cmax25}$ and $m_{bb} = 8$ in a fully-coupled simulation would lead to similar results at Wind River could not be verified. Excessive productivity was found during the 1850–2006 transient simulation, indicating that a smaller V_{cmax25} downscaling factor was necessary. We were able to get similar model results with the alternative nitrogen limitation scheme (in comparison with the default scheme and $m_{bb} = 6$) using $m_{bb} = 9$ and a seasonally-varying V_{cmax25} downscaling factor calculated based on the mean (1850–2006) seasonal cycle of $\mathrm{GPP}/\mathrm{GPP}_{\mathrm{pot}} = 1 - d$ (from simulation using default nitrogen limitation scheme and $m_{bb} = 6$) subtracted by 0.35 (manual adjustment to avoid excessive productivity during the transient simulation). The results are included in the revised paper (Fig. A3).

3. [RC2.1.3] *The authors question the veracity of the observations twice, with regard to H for 1998---2003, and SWC for 1998---2002. I urge extreme caution here, and sincerely hope the authors have corresponded with Dr. Wharton to express their concerns and make these statements with the understanding and approval of the site PI. This is the kind of situation that can foster distrust and animosity between the observational and modeling communities. I most strongly recommend that the authors verify that there may be uncertainty in these observational records, and the listing of Dr. Wharton as a coauthor would legitimize the claims as stated in the MS and confirm that she has participated in discussions of this issue.*

   A: As mentioned in P9L11–15, our remarks on the sensible heat flux (H) observations are based on publicly available information posted on the AmeriFlux database. For clarity, we will add the full URL in the revised text: ftp://cdiac.ornl.gov/pub/ameriflux/data/Level4/Sites_ByName/Wind_River_Field_Station/history_changes.txt

   Our remarks on the soil water content (SWC) data (P12L1–5 and P12L13–22) are based on discussions we carried out with Dr. Ken Bible, the site PI responsible for data management and who was directly involved with the installation of the ground instrumentation. Dr. Bible is a co-author in our paper.

Manuscript revision

We noticed that the document cited above is no longer available online after migration of AmeriFlux to LBNL, so the web link was not included in the revised text.

4. [RC2.1.4a] *Isotopes are difficult. They are difficult to explain, and difficult to understand for many (if not most) readers. The provenance of the treatment of carbon isotopes in CLM is poorly summarized in this MS. Oleson et al. (2013) does not mention them; is Mao (2016) the seminal paper? What about Randerson et al. (2002) or Suits et al. (2005) which investigated isotopes using SiB, or the work of Van der Velde et al. (2013, 2014) which studies isotopes in SiB--- CASA? Did isotopes in CLM build from that work, or from an independent source? R16 is cited, but elaboration is warranted, especially with regard to superposition of an annual cycle onto the larger trend in forcing data.*

   A: Note that Oleson et al. (2013) does indeed describe the treatment of carbon isotopes in CLM 4.5 (see their Chapter 25, p. 391–397). We cite this technical report in P3L21. As stated in P4L6, the implementation of C3 photosynthetic ^{13}C discrimination in CLM follows the model proposed by Farquhar and Richards (1984) and consists of Eqs. (4) and (5). CLM 4.5 does not include any representation of post-photosynthetic discrimination. The rest of the isotopic dynamics is described through the handling of the accounting and conservation of the isotopic pools, with the one exception of nighttime autotrophic respiration, as described in more detail below. The original implementation of ^{13}C in CLM was done in consultation with Neil Suits. We will acknowledge this in the revised paper with the Reviewer's suggested citation (Suits et al. 2005).

With regards to the transient $\delta^{13}CO_2$ forcing data, as mentioned in P6L22–25, we used values based on ice-core and flask measurements reported by Francey et al. (1999) (annual values in their spline fitting from 1850 to 1981) and flask measurements in Mauna Loa (annual averages from 1981 to 2006) by the Scripps CO_2 program (Keeling et al., 2005), following a similar methodology as in Raczka et al. (2016). It is important to clarify that, unlike in Raczka et al. (2016), here we did not superimpose a seasonal cycle onto the time series. We will add this clarification in the revised paper.

Manuscript revision

We acknowledged Suits et al. (2005) in P6L7 and added the clarification on the transient $\delta^{13}CO_2$ forcing data in P9L11.

[RC2.1.4b] *The treatment of $\delta^{13}C_{ER}$ in models is extremely difficult to capture. Heterotrophic respiration is comprised of old, intermediate, and young components, and the $\delta^{13}C$ of each is difficult to constrain, as is the fractional contribution of each. The description of $\delta^{13}C_{ER}$ in section 3.3.1 is troubling; if I understand this section correctly, $\delta^{13}C_{ER}$ follows $\delta^{13}C_{GPP}$ in the daytime, then switches to follow $\delta^{13}C_{HR}$ at night. If the $\delta^{13}C$ of the C_{XS} pool has no sensitivity to recent discrimination, then I assume the pool is large enough that the $\delta^{13}C$ of this pool reflects some previous state. Is this true? What is that state? Is it realistic? The MS states that this behavior "aligns with expectations", but is it realistic? Is this behavior observed at sites with more detailed observations? If this behavior is not observed anywhere, how can you trust the model results?*

A: As shown in Fig. 4, autotrophic respiration (AR) was the major component of total ecosystem respiration (ER), so $\delta^{13}C_{ER}$ exhibited a similar behavior compared to $\delta^{13}C_{AR}$. $\delta^{13}C_{AR}$ followed $\delta^{13}C_{GPP}$ during daytime as daytime maintenance respiration in CLM is fueled by newly assimilated carbon (supplemented by the CS_{xs} pool if GPP is insufficient to meet the demand). During nighttime, $\delta^{13}C_{AR}$ followed values close to $\delta^{13}C_{HR}$ (heterotrophic respiration), with little sensitivity to recent ^{13}C discrimination.

In CLM, carbon from the CS_{xs} pool is used to fuel the maintenance respiration at night (and other periods when GPP is insufficient to meet the maintenance respiration demand, e.g. winter). This is called "excess maintenance respiration", or XSMR, in the model. The nighttime $\delta^{13}C_{AR}$ therefore follows $\delta^{13}C_{XSMR}$. However, the isotopic signature of XSMR is not taken from CS_{xs}, but from the bulk vegetation tissues (total vegetation carbon, TOTVEGC). This is done because CS_{xs} is not a physical quantity, but a construct of CLM. Note that XSMR "borrows" carbon from the CS_{xs} pool, which is allowed to run a deficit state. This "debt" is paid in the future with the replenishment of the CS_{xs} pool with newly assimilated carbon. This construct makes the $\delta^{13}C$ of CS_{xs} non-physical, therefore, the approximation that $\delta^{13}C_{XSMR}$=$\delta^{13}C_{TOTVEGC}$ is more physically realistic.

In summary, the approximation done in the model ($\delta^{13}C_{XSMR}$=$\delta^{13}C_{TOTVEGC}$) makes the nocturnal $\delta^{13}C_{AR}$ to follow $\delta^{13}C_{TOTVEGC}$. This explains the low sensitivity of the nocturnal $\delta^{13}C_{AR}$ to recent

^{13}C discrimination in our results (Fig. 4b). We will revise our explanation given in P10L12–16 with this information.

In P10L15 we mention that “the simulation results in Fig. 4b align with these expectations”. Please note that the “expectations” which we refer to are related to the understanding of the carbon allocation structure in the model, not to observations. Observations at Wind River indicate that AR is likely fueled by a mixture of stored and recently-fixed carbon (P10L17), a process that cannot be appropriately modeled with the current carbon allocation scheme in CLM, given the lack of an explicit representation of carbohydrate storage pools to support maintenance respiration. In P10L17–22 we discuss this limitation in the model and highlight the need for a better representation of carbohydrate storage pools within CLM. In P11L20 we also point out that the implementation of carbon isotopes in CLM opens an interesting opportunity for future model development, as isotopes expose a limitation of the carbon allocation scheme. In future efforts, carbon isotope data can be used to guide a restructuring of the model, moving away from the deficit-based accounting scheme towards an explicit representation of carbohydrate storage pools.

Manuscript revision

We revised the explanation of the CS_{xs} pool and its implications to the isotopic signature of autotrophic respiration, as discussed above (P13L27–P14L3).

[RC2.1.4c] *Similarly, the authors state that “Autotrophic respiration at Wind River is likely fueled by a mixture of stored and recently---fixed carbon, as indicated by* ^{14}*C measurements…(and) cannot be appropriately modeled by CLM with the current allocation scheme…” so if I understand correctly, we can’t trust the* $\delta^{13}C_{HR}$ *because CLM doesn’t consider different contributions from differently---aged dead pools, and we can’t trust the* $\delta^{13}C_{AR}$ *either. Both* $\delta^{13}C_{AR}$ *and* $\delta^{13}C_{HR}$ *influence the* $\delta^{13}C$ *of the canopy air, which will in turn have a strong influence on* $\delta^{13}C_{GPP}$*! At this point I’m left thinking that we have no confidence in any of the discrimination values of this version of CLM, and any resemblance to observations is a happy accident.*

A: CLM does not consider different age classes of decomposing material. Instead, it treats different classes of litter and soil organic matter quality, with characteristic decomposition rates. It is possible to track a labeled pulse through these various pools because they are connected in a cascade structure, but it is not possible to isolate a specific age-class or cohort of same-aged decomposing material without rather elaborate “numerical labeling” experiments.

The main issue (or at least the most obvious one) is not with the representation of $\delta^{13}C_{HR}$ (heterotrophic respiration), but with the representation of $\delta^{13}C_{AR}$ (autotrophic respiration), for the reasons discussed in our response above. The isotopic signature of the total ecosystem respiration (ER=AR+HR) is obviously affected. However, in CLM, there is no feedback onto the canopy air space, because there is no prognostic canopy air space to feed back onto. This is unlike the SiB model, for instance, which does have a prognostic canopy airspace. Therefore, in CLM, $\delta^{13}C_{GPP}$ is not affected. We will add this discussion in the revised paper.

Manuscript revision

We added in the revised manuscript (P14L10–12): "It is important to highlight that, unlike models such as SiB (Sellers et al., 1996; Vidale and Stöckli, 2005), CLM does not have a prognostic canopy airspace where $\delta^{13}CO_2$ is impacted by photosynthetic and respiratory fluxes, so the simulation of $\delta^{13}C_{GPP}$ is not affected by the above described limitations in the simulation of $\delta^{13}C_{ER}$."

[RC2.2] *I do not recommend rejection, but this paper requires major revisions to be acceptable for publication. The differences between the findings at Wind River and those of R16 must be reconciled, and the problems with the isotope treatment must be resolved. Furthermore, the characterization of climatological dry summer as 'drought' is unacceptable.*

A: We addressed these topics in our responses above.

Specific Comments

- [RC2.3] *The plant wilting factor, w_i, can be expressed in a multitude of ways, and could have serious implications for this site. Entekhabi and Eagleson (1989) suggest a linear reduction in w_i from some point s* below field capacity (where w_i = 1) to a value of 0 at wilt point, while Sellers et al (1996) and Colello et al (1998) promote a nonlinear equation for w_i based on field data from FIFE. Baker et al (2008) demonstrate that in tropical forests, a direct linkage of w_i to the vertical profile of root density can be problematic. What form does w_i take in CLM? Neither R16 nor this manuscript discuss this; was it investigated? This suggests yet another path that can be taken to tune CLM. More equifinality.*

  A: In our answer to RC1.3 we describe how the plant wilting factor (w_i) is calculated in CLM. We agree that w_i offers a path for adjustment of the soil moisture stress factor (β_t). In our study we opted to adjust the root distribution (r_i) instead, shifting it to deeper soil layers (a physically justified approach – see further discussion in our response to RC1.13). We have not investigated the w_i factor in our study, but will include its formulation and point out that it offers an additional path that can be taken to adjust β_t.

Manuscript revision

We added the equation for w_i in the revised manuscript (Eq. 5). We also included: "The plant wilting factor, w_i, offers an additional path for adjustment of the simulated soil moisture stress, but it was not investigated in this study." (P25L30–31).

- [RC2.4] *Discussing equation 5, the authors state that since $g_b >> g_s$, g_b can be neglected in the calculation of ci/ca, and therefore discrimination. In midday this is certainly true, but what about near sunrise/sunset, particularly sunrise? I can imagine that immediately after sunrise, the canopy is cool and the nocturnal inversion has not yet been broken. The canopy, however,* *is illuminated, and both temperature and humidity are favorable for stomatal conductance. In this situation I might expect that g_s could be larger than g_b. This might also have some bearing on the large excursions in $\delta^{13}C_{GPP}$ values seen early and late in the day. Was this investigated?*

A: We would like to clarify that Eq. (5) is the actual equation used in the model, and Eq. (6) is a simplification we presented for discussion purposes. We did check the modeled values of leaf boundary-layer conductance (g_b) against the modeled values of leaf stomatal conductance (g_s). We found g_b to be much larger than g_s, even around sunrise and sunset.

- [RC2.5] *Line 31, page 6; should be 'resulting', not 'resulted'*

  A: We will make the correction in the text.

Manuscript revision

Correction made.

- [RC2.6] *Why is the observed $\delta^{13}C$ of bottom canopy leaves so much lower than elsewhere in the canopy? Does this inform the CLM treatment of isotopes?*

  A: Please see our answer to RC1.10.

- [RC2.7] *ET will be composed of transpiration, leaf evaporation and ground evaporation components. In a dense canopy like Wind River, I would expect ground evaporation to be low, but excessive leaf evaporation could influence the amount of infiltration and therefore the amount of water available for transpiration later in the season. What is the partition of these components at Wind River? I know it is impossible to quantify these components with a single ET observation, but the model partition may give insight into behavior.*

  A: Overall, the simulated ground evaporation (FGEV) was negligible in respect to the simulated canopy transpiration (FCTR) and canopy evaporation (FCEV) (Fig. R3). FCTR was very low during winter and peaked during summer. On the other hand, FCEV was a major component of ET during the wet season (~October–May) but typically presented very small values during the dry season in summer. The results in Fig. R3 (year 2005) illustrate the overall pattern.

  In this study we were able to reasonably simulate the observed soil water content (SWC) values during summer with the adjustment of the soil hydraulic parameters (see P11L30 and Sect. A7). Perhaps the dry bias we found in SWC during summer when using the original soil hydraulic parameters could be in part related to excessive interception of precipitation by the canopy (and reduced infiltration), as pointed out by the reviewer. The observations we have do not allow us to evaluate if the simulated FCEV values were excessive, though. A sensitivity test to see how the simulated summer SWC values are impacted by the modeling of FCEV and eventual adjustments using this path are out of scope here, but are suggested for future studies.

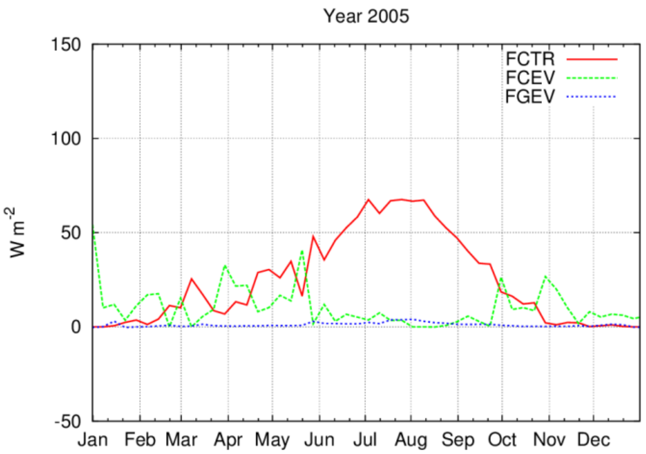

Fig. R3: Partitioning of evapotranspiration at Wind River, as modeled by CLM. FCTR is canopy transpiration, FCEV is canopy evaporation, and FGEV is ground evaporation. Lines correspond to 1-hourly data, smoothed via a Bézier algorithm, for year 2005.

- [RC2.8] *The authors mention a "spring---to---summer decrease in the contribution of root respiration towards total soil respiration". That makes me think that the observed signal could come about from one of 2 ways. 1) there is a decrease in discrimination as WUE increases, or 2) there is an increase in the HR component towards older material with a lower $\delta^{13}C$. Is this possible?*

A: Assuming the Reviewer is referring to the observed $\delta^{13}C_{ER}$ (ecosystem respiration) signal and meant "higher $\delta^{13}C$" in explanation 2 (^{13}C:^{12}C ratio is higher for older carbon given the Suess effect), that interpretation is correct. In fact, we already discuss this in the paper (P10L31–P11L3):

"The seasonal pattern in the observed $\delta^{13}C_{ER}$ (Fig. 5) could be partially attributed to an eventual spring-to-summer decrease in AR:ER ratio (assuming $\delta^{13}C_{HR} > \delta^{13}C_{AR}$). ^{14}C measurements from below-ground respiration components at Wind River reported by Taylor et al. (2015) do indicate a spring-to-summer decrease in the contribution of root respiration (RR) towards total soil respiration (SR=RR+HR). The similarity of the seasonal patterns of observed $\delta^{13}C_{ER}$ and modeled $\delta^{13}C_{GPP}$ suggests that stomatal response to drought[#] could also be driving the seasonal pattern in the observed $\delta^{13}C_{ER}$ at the site".

Note that a decrease in AR:ER is equivalent to say an increase in HR:ER. Note also that by "stomatal response to drought[#]" we mean a decrease in stomatal conductance leading to higher water use efficiency and lower photosynthetic ^{13}C discrimination.

[#] Will be reworded to "water stress" in the revised paper, avoiding confusion with meteorological drought (precipitation below climatological normal). See our response to RC2.1.1.

- [RC2.9] *When discussing soil moisture, fraction of saturation may be more useful than volumetric water content. The volumetric content at various important points (wilt point, field capacity, saturation) can vary significantly depending on soil character.*

  A: At Wind River, volumetric soil water content (SWC) at permanent wilting point is 14%, and SWC at field capacity is 30% (Wharton et al. 2009). We will include this information in the discussion.

Manuscript revision

Information included in P15L23–24 and in the caption of Fig. 6.

- [RC2.10] *Page 13, lines 14---17: "Observed $\delta^{13}C_{ER}$ was found to have a low negative correlation with observed G_c, but not statistically significant. The low correlation was likely a result of $\delta^{13}C_{ER}$ reflecting constraints of prior environmental drivers in comparison with the more rapid response of G_c to more recent environmental drivers." This is not surprising, but doesn't it underscore the importance of getting a handle on all these drivers, in both your observations and model? Aren't you basically saying here that the model results are not to be trusted because the proper mechanistic pathways for the various isotopes are not simulated?*

  A: Indeed, the simulated $\delta^{13}C_{ER}$ (ecosystem respiration) values are impacted by the lack of an explicit representation of carbohydrate storage pools within CLM to support the maintenance respiration demand (see our answer to RC2.1.4). Note that the $\delta^{13}C_{ER}$ observations correspond to nocturnal measurements. During nighttime, our modeled $\delta^{13}C_{ER}$ values were found to be virtually constant throughout the entire study period (1998—2006), with values similar to $\delta^{13}C_{HR}$ (heterotrophic respiration) (Fig. 4b). During daytime, modeled $\delta^{13}C_{ER}$ was similar to $\delta^{13}C_{GPP}$ (gross primary production). Note that in Fig. 9b we plotted modeled $\delta^{13}C_{GPP}$, not modeled $\delta^{13}C_{ER}$, versus modeled canopy conductance (G_c) in order to have a more informative result for comparison against Fig. 9a (observed $\delta^{13}C_{ER}$ vs. observed G_c; see discussion in P13L12–21).

Comments from Associate Editor

Dear Authors
Thank you for your very careful response to the reviews of the first version of the manuscript. At this stage I would recommend to go ahead with providing a revision that carefully addresses the many critical points the referees have raised.

When you work on the revision please keep specifically in mind:
1. That trial and error model tuning is never superior to Bayesian calibration. In accepting that calibrating the model properly was not possible, you accept that the information to constrain the complex model is not sufficient and, thus, the information on the generated parameters meaningless, i.e. one of potentially many possible solutions with no information on the parameter

uncertainty and correlation with other parameters. In your response you seem to neglect this deficiency when writing: “The calibrated parameters we present in the paper may be of use for future modelling studies”. How can parameters that have been generated in a trial and error fashion be acceptable for the modelling community?

A: We no longer include those statements. In the revised manuscript we focus on the adjustment of the Ball-Berry stomatal conductance slope at Wind River and compare our results against those from other recent CLM studies at sites characterized by the same plant functional type as Wind River (needleleaf evergreen temperate tree), but significant differences in stand composition/age and climatology. The comparison shows an agreement across the sites, suggesting that CLM could benefit from a revised (lower) stomatal slope for that PFT.

2. A very important concern is that both reviewers have expressed their impression that you didn’t motivate the study well enough. When you prepare the revision please make sure that the objectives of your study can be easily understood and are well reasoned. Clarification of the objectives and the achieved scientific progress will be an essential requirement for the acceptance of the manuscript. A statement ‘represent important contributions to the modeling community’ is not explicit enough.

A: We carefully followed the recommendation from Reviewer 1:

1. Introduction was significantly revised. Additional citations were included, helping to more clearly lay out the motivation of our study.

2. Discussion of results was expanded. A separate “Discussion” section was created (Sect. 4), where we focus on the key findings of our study.

Abstract and Conclusion were revised accordingly.

With kind regards,
Andreas Ibrom

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Evaluating the Community Land Model (CLM 4.5) at a Coniferous Forest Site in Northwestern United States Using Flux and Carbon-Isotope Measurements

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Abstract. Droughts~~Summer droughts~~ in the western United States are expected to intensify with climate change. Thus, an adequate representation of ecosystem response to water stress~~drought response~~ in land models is critical for predicting carbon dynamics. The goal of this study was to evaluate~~assess~~ the performance of the Community Land Model, Version 4.5 (CLM) against observations at~~for~~ an old-growth coniferous forest site in the Pacific Northwest region of the United States (Wind River AmeriFlux site), characterized by a Mediterranean climate that subjects trees to water stress each summer~~ that has heavy winter precipitation followed by summer drought. Particular attention was given to the model skill in the simulation of stomatal conductance and its response to drought stress~~. CLM was driven by site-observed meteorology and calibrated primarily using parameter values observed at the site or at similar stands in the region. Key model adjustments included parameters controlling specific leaf area and stomatal conductance. Default values of these parameters led to significant underestimation of gross primary production, overestimation of evapotranspiration, and consequently overestimation of photosynthetic ^{13}C discrimination, reflected on reduced ^{13}C:^{12}C ratios of carbon fluxes and pools. Adjustments in soil hydraulic parameters within CLM were also critical, preventing significant underestimation of soil water content and unrealistic soil moisture~~drought~~ stress during summer. After calibration, CLM was able to simulate energy and carbon fluxes, leaf area index, biomass stocks, and carbon isotope ratios of carbon fluxes and pools in reasonable agreement with site observations. Overall, the calibrated CLM was able to simulate the observed response of canopy conductance to atmospheric vapor pressure deficit (VPD) and soil water content, reasonably capturing the impact of water~~drought~~ stress on ecosystem functioning. Both simulations and observations indicate that stomatal response from water stress at Wind River was primarily driven by VPD and not soil moisture.~~ The calibrated parameters may be of use for future modeling studies involving stands of similar age and composition under a similar climate regime.~~ The calibration of the Ball-Berry stomatal conductance slope (m_{bb}) at Wind River aligned with findings from recent CLM experiments at sites characterized by the

Comment [HFD1]: [RC1.2]

same plant functional type (needleleaf evergreen temperate forest), despite significant differences in stand composition/age and climatology, suggesting that CLM could benefit from a revised m_{bb} value of 6, rather than the default value of 9, for this plant functional type. On the other hand, Wind River required a unique calibration of the hydrology submodel to simulate soil moisture, suggesting the default hydrology has a more limited applicability. ~~More broadly, the calibration of the Ball-Berry stomatal conductance model in CLM aligned with observations reported in the literature for coniferous trees, suggesting that a future release of CLM would benefit from using a distinct, lower slope value ($m_{bb} = 6$) for conifers, rather than a unique value for all C3 plants ($m_{bb} = 9$).~~ This study demonstrates that carbon isotope data can be used to constrain stomatal conductance and intrinsic water use efficiency in CLM, as an alternative to eddy covariance flux measurements. It also demonstrates that carbon isotopes can expose structural weaknesses in the model and provide a key constraint that may guide future model development. ~~Thanks to the recent implementation of photosynthetic ^{13}C discrimination within CLM, the results of this study indicate that carbon isotope measurements can be used to constrain stomatal conductance and water use efficiency in CLM as an alternative to flux observations. They also have the potential to guide structural improvements in the model in respect to the representation of carbon storage pools.~~

1 Introduction

The frequency, duration, and severity of droughts are expected to increase in the 21st century with climate change (Burke et al., 2006; Sheffield and Wood, 2008; Dai, 2013; Prein et al., 2016). In the western United States in particular, the combination of warmer temperature, larger vapor pressure deficit, reduced snowfall and snow pack, earlier snow melt, and extended growing season length is expected to lead to an intensification of water stress during the summer ~~summer droughts~~ (Boisvenue and Running, 2010; Spies et al., 2010; Swain and Hayhoe, 2015; Fyfe et al., 2017). In this drying scenario, an accurate representation of ecosystem response to water stress~~drought response~~ in land models is critical for projecting carbon dynamics (and climate) into the future.

The land carbon and water cycles are coupled by the plant stomata through CO$_2$ uptake (photosynthesis) and water vapor loss (transpiration)~~Leaf gas exchange, including CO$_2$ uptake from photosynthesis and water vapor loss via transpiration, is controlled by leaf stomata~~. While s~~S~~tomatal conductance responds to atmospheric vapor pressure deficit, soil moisture, and various other environmental factors~~drought and various other environmental factors~~, ~~but~~ its modeling still represents a major challenge for the scientific community (Damour et al., 2010). Many stomatal conductance models have been proposed, including different approaches to account for water~~drought~~ stress, but each model is subject to~~has~~ its own limitations (~~see the detailed review by~~ Damour et al., 2010; Miner et al., 2017; Sperry et al., 2017). Traditionally, stomatal conductance models have been calibrated through leaf to canopy-level observations of water exchange.

Stable carbon isotopes provide an alternative observation to constrain stomatal conductance and offer an opportunity for model evaluation and improvement. During photosynthesis, plants discriminate against the heavier stable isotope of carbon (^{13}C) in favor of the lighter, more abundant ^{12}C stable isotope. This discrimination in C$_3$ plants, expressed

Comment [HFD2]: [RC1.2]

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as $\Delta = [(R_{air}/R_{plant}) - 1] \times 1000$ (‰), where R_{air} and R_{plant} are the ^{13}C:^{12}C isotope ratios of atmospheric CO_2 and plant assimilated carbon, respectively, can be estimated according to the model proposed by Farquhar and Richards (1984) as

$$\Delta = a + (b - a)c_i/c_a\,, \tag{1}$$

where c_i/c_a is the ratio of intra~~er~~cellular CO_2 concentration to atmospheric CO_2 concentration, a is the ^{13}C discrimination associated with the process of CO_2 diffusion through the stomata, and b is the ^{13}C discrimination associated with the process of assimilation of CO_2 via Rubisco ($a \approx 4.4‰$ and $b \approx 27‰$; Farquhar et al., 1989). The c_i/c_a ratio correlates negatively with leaf intrinsic water use efficiency (iWUE), defined as the ratio of net leaf assimilation to stomatal conductance (Farquhar et al., 1989). Under water stress~~drought stress~~, C_3 plants tend to reduce stomatal conductance and increase water use efficiency, leading to reductions in c_i/c_a and ^{13}C discrimination, affecting the carbon isotope ratio ($\delta^{13}C$) of photosynthesis~~ate~~ and consequently of carbon pools and respiration~~fluxes~~. Experimental studies have shown, for instance, correlations between the $\delta^{13}C$ of ecosystem respiration and soil water content, atmospheric vapor pressure deficit, and precipitation. ~~(see~~ Bowling et al. (~~,~~ 2008) and Brüggemann et al. (~~,~~ 2011) present~~for~~ extensive reviews of experimental results on the link between environmental factors and the isotopic signature of carbon pools and fluxes~~).~~, demonstrating that isotopic measurements provide insights into the response of stomatal conductance and iWUE to water stress. Furthermore, stable carbon isotopes have been used to partition photosynthetic and respiration fluxes from flux tower data (e.g., Wehr and Saleska, 2015) and to identify the strength of land and ocean sinks (e.g., Alden et al., 2010; van der Velde et al., 2013).

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~~Isotopic measurements can therefore be used to gain insights about the response of stomatal conductance and water use efficiency to drought.~~ Photosynthetic ^{13}C discrimination is represented in biospheric models including the stable isotope-enabled Land Surface Model, ISOLSM (Riley et al., 2002), the Simple Biosphere Model, SiB (Suits et al., 2005), the Lund-Potsdam-Jena dynamic global vegetation model, LPJ (Scholze et al., 2003; 2008), the Land Surface Processes and Exchanges model of the University of Bern, LPX-Bern (Spahni et al., 2013; Stocker et al., 2013), the hybrid SiB-CASA (combining biophysics from SiB and biochemistry from the Carnegie-Ames-Stanford Approach model) (van der Velde et al., 2013; 2014), and the Community Land Model, CLM (Oleson et al., 2013).

Modeling studies have shown that stable carbon isotopes provide a constraint upon stomatal conductance (Aranibar et al., 2006; Raczka et al., 2016; Mao et al., 2016). Aranibar et al. (2006) evaluated the performance of ISOLSM at the Metolius Old Pine AmeriFlux site and were able to calibrate the slope of the stomatal conductance equation (m_{bb} in the Ball-Berry stomatal conductance model; see Eq. 2) with the aid of foliar $\delta^{13}C$ data measured at the site. Raczka et al. (2016) evaluated photosynthetic ^{13}C discrimination in CLM version 4.5 (CLM4.5) against $\delta^{13}C$ observations of photosynthesis and biomass at the Niwot Ridge AmeriFlux site and found the model to perform poorly with its default nitrogen limitation approach, resulting in overestimation of stomatal conductance and ^{13}C discrimination. By using an alternative approach in which a nitrogen downscaling factor is directly applied to V_{cmax25} (maximum rate of carboxylation at 25°C), they found significant improvement in the simulations, but with results still suggesting that a smaller m_{bb} value (they used the default C_3 value, $m_{bb} = 9$) would better simulate the site observations. Mao et al. (2016) evaluated CLM4.0 at a loblolly pine site in

Comment [HFD3]: [RC2.1.2]

Tennessee, USA and were able to adequately simulate the observed biomass δ^{13}C values with an optimized m_{bb} value of 5.6. Keller et al. (2017) used a global tree-ring δ^{13}C dataset to evaluate the 20th-century trend in photosynthetic ^{13}C discrimination and iWUE as modeled by CLM4.5 and LPX-Bern. LPX-Bern was found to perform well, while CLM simulated a significantly stronger increase (decrease) in iWUE (^{13}C discrimination) than that indicated by the tree-ring data. The default CLM parameterization and configuration were used in their study. Keller et al. (2017) suggested that the model-data mismatch was associated with the stomatal conductance parameterization (m_{bb} in particular) and the shortcomings of the nitrogen limitation scheme.

The present study focuses on CLM —the land component of the Community Earth System Model (CESM), a fully-coupled global climate model widely used by the scientific community (http://www.cesm.ucar.edu/publications/)— and further evaluates the performance of its latest release (CLM4.5 – hereafter referred simply as "CLM") against observations at a coniferous forest site in the Pacific Northwest region of the United States

~~Photosynthetic ^{13}C discrimination has been included in the latest release of the Community Land Model (CLM v.4.5, hereafter referred to as CLM). CLM is the land model component of the Community Earth System Model (CESM), a fully-coupled, global climate model widely used by the scientific community. Revised photosynthesis and hydrology schemes, among an extensive list of updates have also been included in CLM (Oleson et al., 2013).~~

~~The goal of the present study is to evaluate the performance of CLM for a coniferous forest site in the Pacific Northwest region of the United States (Wind River AmeriFlux site)~~, with particular attention to the simulation of stomatal conductance and its response to water stress~~changes in atmospheric vapor pressure deficit and soil water content associated with summer drought~~. The study site, Wind River, is part of the AmeriFlux eddy covariance network. Wind River is an old-growth forest (~500 years) characterized by a Mediterranean climate, due to which trees are naturally subject to water stress each summer. The combination of long-term measurements of energy/carbon fluxes, meteorology, biological variables, and stable carbon isotope ratios, make the site a good choice for evaluating carbon cycle and carbon isotope components of CLM. In addition to energy flux observations which allow for the estimation of canopy conductance, this study leverages the recent inclusion of photosynthetic ^{13}C discrimination within CLM and also uses δ^{13}C observations to better diagnose the simulation of stomatal conductance at the site. We test whether a reduced stomatal conductance at similar needleleaf evergreen temperate forest sites (Mao et al., 2016; Raczka et al., 2016) is appropriate for Wind River. This study also provides further investigation on the nitrogen limitation issue identified by Raczka et al. (2016) and the adequacy of the default parameters used in CLM, especially those regulating stomatal conductance. We test whether the calibration scheme (optimized parameters, nitrogen limitation) proposed by Raczka et al. (2016) for Niwot Ridge, is appropriate for Wind River. By comparing the results at Wind River against those at different sites characterized by the same plant functional type (needleleaf evergreen temperate tree) but with different stand composition/age and climatology (Mao et al., 2016; Raczka et al., 2016), this study also seeks to identify general improvements in model parameterization.~~For this evaluation, this study uses not only observed surface fluxes, leaf area index, and biomass stocks as reference values, but also observed δ^{13}C values of carbon fluxes and pools, taking advantage of the recent inclusion of photosynthetic ^{13}C discrimination within the model.~~

2 Material and Methods

This Section provides a description of CLM, focusing on key formulations of relevance to the present study (Sect. 2.1), followed by a description of the study site (Sect. 2.2), the eddy-covariance and meteorological data sets used to drive and assess the model (Sect. 2.3), the carbon isotope data sets used to assess the photosynthetic ^{13}C discrimination in CLM (Sect. 2.4), and also a description of the CLM configuration, simulations performed, and calibration of model parameters (Sects. 2.5 and 2.6). Section 2.7 describes the methodology used in the calculation of canopy conductance values from eddy-covariance observations, which are compared against simulated values as a way to assess the model skill in simulating leaf stomatal conductance.

2.1 Model Description

This Section focuses on describing CLM's approach to the simulation of stomatal conductance and photosynthetic ^{13}C discrimination, key aspects of this study. For a full description of the model, the reader is referred to Oleson et al. (2013).

In CLM, leaf stomatal conductance (g_s) is calculated based on the Ball-Berry model as described by Collatz et al. (1991) and implemented by Sellers et al. (1996) in the SiB2 model:

$$g_s = m_{bb} \frac{A_n(\beta_t)}{c_s/P_{atm}} h_s + b_{bb}\beta_t \qquad (2)$$

where $A_n(\beta_t)$ is the potential net leaf photosynthesis (without nitrogen limitation) as a function of a soil moisture~~drought~~ stress factor (β_t), c_s is the CO$_2$ partial pressure at the leaf surface, P_{atm} is the atmospheric pressure, h_s is the relative humidity at the leaf surface (defined as the ratio of vapor pressure at the leaf surface to saturation vapor pressure inside the leaf at vegetation temperature T_v), m_{bb} is a slope coefficient, and b_{bb} corresponds to the minimum stomatal conductance in the original Ball-Berry model. The soil moisture~~drought~~ stress factor β_t is defined as:

$$\beta_t = \textstyle\sum_i w_i r_i \qquad (3)$$

where r_i is the root fraction at soil layer i and w_i is a corresponding plant wilting factor. The former is defined as (Oleson et al., 2013):

$$r_i = 0.5\left(e^{-r_a z_{h,i-1}} + e^{-r_b z_{h,i-1}}\right) - 0.5\alpha\left(e^{-r_a z_{h,i}} + e^{-r_b z_{h,i}}\right) \qquad (4)$$

where $z_{h,i}$ (m) is the depth from the soil surface to the interface between layers i and $i+1$ ($z_{h,0} = 0$ corresponds to the soil surface), r_a and r_b are root distribution parameters (m^{-1}), $\alpha = 1$ for $1 \leq i < N_{levsoi}$, and $\alpha = 0$ for $i = N_{levsoi}$ (N_{levsoi} is the number of soil layers). The plant wilting factor for soil layer i is defined as (Oleson et al., 2013):

Comment [HFD4]: [RC1.3], [RC2.3]

$$w_i = \begin{cases} \frac{\Psi_c - \Psi_i}{\Psi_c - \Psi_o}\left[\frac{\theta_{sat,i} - \theta_{ice,i}}{\theta_{sat,i}}\right] \leq 1 & \text{for } T_i > T_f - 2 \text{ and } \theta_{liq,i} > 0 \\ 0 & \text{for } T_i \leq T_f - 2 \text{ or } \theta_{liq,i} = 0 \end{cases} \qquad (5)$$

where Ψ_i is the soil water matric potential, Ψ_c and Ψ_o are the soil water potential when stomata are fully closed or fully open, respectively ($\Psi_c = -255000$ mm and $\Psi_o = -66000$ mm for the needleleaf evergreen temperate tree plant functional type, hereafter referred simply as "NETT PFT"), $\theta_{sat,i}$ is the saturated volumetric water content, $\theta_{ice,i}$ is the volumetric ice content, $\theta_{liq,i}$ is the volumetric liquid water content, T_i is the soil layer temperature, and $T_f = 273.15$ K is the freezing temperature of water.~~, calculated as a function of soil water potential and a plant-dependent response to drought stress.~~ The sum in Eq. (3) is defined over the entire soil column, resulting in β_t values from 0 (maximum soil moisture~~drought~~ stress) to 1 (no ~~drought~~ soil moisture stress). In CLM's implementation of the Ball-Berry model (Eq. 2), β_t is used to downscale b_{bb}, directly impacting g_s. β_t also indirectly impacts g_s through the A_n term, as β_t is used to downscale the maximum rate of carboxylation ($\beta_t V_{cmax}$) and also leaf respiration ($\beta_t R_d$) (Oleson et al., 2013).

Stomatal conductance (g_s) and A_n are solved separately for sunlit and shaded leaves. Canopy conductance (G_c) is given by

$$G_c = \frac{1}{r_b + r_s^{sun}} \mathrm{LAI}^{sun} + \frac{1}{r_b + r_s^{sha}} \mathrm{LAI}^{sha} \tag{6}$$

and potential gross primary production (GPP$_{\mathrm{pot}}$, without nitrogen limitation) by

$$\mathrm{GPP_{pot}} = (A_n^{sun} + R_d^{sun})\mathrm{LAI}^{sun} + \left(A_n^{sha} + R_d^{sha}\right)\mathrm{LAI}^{sha} \tag{7}$$

where r_b is the leaf boundary layer resistance, $r_s = 1/g_s$ is the leaf stomatal resistance, LAI is the leaf area index, and R_d is the leaf-level respiration (sun and sha superscripts denote sunlit and shaded leaves, respectively). Photosynthetic parameters such as V_{cmax25} are solved separately for sunlit and shaded leaves and their canopy scaling scheme is detailed in Oleson et al. (2013, Sect. 8.3).

Based on nitrogen availability and nitrogen requirements for allocation of new carbon tissue, CLM calculates actual GPP as

$$\mathrm{GPP} = \mathrm{GPP_{pot}}(1 - d) \tag{8}$$

The nitrogen down-regulation factor (d) is defined as

$$d = \frac{\mathrm{CF_{avail\_alloc}} - \mathrm{CF_{alloc}}}{\mathrm{GPP_{pot}}} \tag{9}$$

where $\mathrm{CF_{avail\_alloc}}$ is the carbon flux from photosynthesis which is available to new growth allocation and $\mathrm{CF_{alloc}}$ is the actual carbon allocation to new growth (limited by nitrogen availability). This implementation of nitrogen down-regulation makes CLM a partially-coupled model with respect to net leaf photosynthesis and stomatal conductance. Note that actual plant gross carbon uptake (GPP) is calculated via down-regulation (Eq. 8) after the solution for A_n and g_s is obtained. Modeled g_s remains consistent with A_n (potential, not actual net leaf photosynthesis).

The original implementation of ^{13}C in CLM was developed in consultation with Neil Suits (Suits et al., 2005) and is described in Oleson et al. (2013). ~~The implementation of P~~photosynthetic ^{13}C discrimination in CLM for C_3 plants follows the model proposed by Farquhar and Richards (1984) (cf. Eq. 1):

$$\Delta = 4.4 + 22.6\, c_i/c_a.$$

(10~~4~~)

CLM calculates the intra~~er~~cellular-to-atmospheric CO_2 concentration ratio, c_i/c_a, in Eq. (10) as:

$$\frac{c_i}{c_a} = 1 - \frac{A_n(1-d)}{c_a}\left[\frac{1.4}{g_b} + \frac{1.6}{g_s}\right]$$

(11~~5~~)

Comment [HFD5]: [RC1.6]

Comment [HFD6]: [RC2.1.4a]

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where ~~d is a downregulation factor associated with nitrogen limitation and~~ g_b is the leaf boundary layer conductance. CLM does not account for mesophyll conductance (intracellular CO_2 is assumed to be the same as intercellular CO_2). Assuming $g_b \gg g_s$ (typically true for coniferous needles), Eq. (11~~5~~) can be approximated by:

$$\frac{c_i}{c_a} \cong 1 - \frac{1.6(1-d)}{c_a}\left[\frac{A_n}{g_s}\right]$$

$$\cong 1 - \frac{1.6(1-d)}{c_a}\text{iWUE}$$

(12~~6~~)

where iWUE $= A_n/g_s$ is the intrinsic water use efficiency. Note that c_i/c_a and consequently Δ correlate negatively with iWUE. All other terms being constant in Eq. (12~~6~~), an increase in iWUE is expected to result in a reduction of the photosynthetic ^{13}C discrimination, i.e., an increase in the assimilation of the heavier ^{13}C stable isotope relative to the lighter, more abundant ^{12}C stable isotope. Note also that A_n is multiplied by $(1-d)$ in Eqs. (11) and (12), making c_i consistent with the actual, nitrogen-limited GPP. However, it is important to highlight that g_s is consistent with A_n (potential net assimilation), not $A_n(1-d)$ (actual net assimilation). The implications of this mismatch to the simulation of Δ are discussed in Raczka et al. (2016) and later in the present paper.

The carbon isotope ratio of the GPP flux ($\delta^{13}C_{GPP}$) is calculated in CLM based on the prescribed δ^{13}C of atmospheric CO_2, the carbon assimilation and photosynthetic ^{13}C discrimination by sunlit and shaded leaves, and their respective leaf area indices. The δ^{13}C of newly allocated carbon is the same as $\delta^{13}C_{GPP}$. The δ^{13}C of the leaf carbon pool, for instance, depends on the allocation flux and its δ^{13}C ($\delta^{13}C_{GPP}$) and the turnover time of the pool. CLM does not include any representation of post-photosynthetic ^{13}C discrimination.

Comment [HFD7]: [RC1.5]

Comment [HFD8]: [RC1.4]

Comment [HFD9]: [RC2.1.2]

Comment [HFD10]: [RC1.6]

2.2 Site Description

The ~~chosen~~ site for this study ~~–~~(Wind River)~~–~~ is part of the AmeriFlux eddy covariance network (Baldocchi et al., 2001) with a long record of meteorological, biological, surface flux (energy and carbon), and carbon isotope measurements for model assessment (1998–present). The site is located in the Pacific Northwest region of the United States, in the state of Washington (45.8205 Lat, −121.9519 Lon, 371-m elevation — see Fig. 1). Wind River is characterized by an old-growth conifer forest dominated by Douglas-fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*) trees, with a mean canopy height of 56 m. Douglas-fir trees are about 40–65-m high, corresponding to about 50% of the wood volume of the stand and 33% of the leaf area, while western hemlock trees are more numerous and smaller, corresponding to about 53% of the leaf area of the stand (Unsworth et al., 2004; Parker et al., 2004). No significant disturbances have occurred at the site in the past ~450–500 years. The local climate is strongly seasonal, marked by dry summers~~annual summer drought~~ and wet winters. The climate summary reported by Shaw et al. (2004) indicates a mean annual precipitation of 2223 mm, with only ≈5% falling during June, July, and August. During winter, much of the precipitation falls as snow, and the average snowpack depth exceeds 100 mm. The mean annual, January, and July air temperatures are 8.7±6.5 °C, 0.1±2.3 °C, and 17.7±1.7 °C, respectively.

2.3 Eddy-Covariance and Meteorological Data

Air temperature, relative humidity, wind speed, incident short-wave radiation, incident long-wave radiation, atmospheric pressure, and precipitation observed at the Wind River site from 1998 to 2006 were used to drive CLM. The time series were gap-filled using data from nearby towers and climate stations or interpolated in case of missing data. The gap-filled data product used to drive CLM in this study was created at Oak Ridge National Laboratory following the methodology described in Barr et al. (2013).

The L4 data set based on the eddy-covariance observations was downloaded from the AmeriFlux repository (version V002, daily averages). This data set contains friction-velocity-filtered, gap-filled, and partitioned fluxes and was used to assess the simulated surface fluxes of sensible heat (H), latent heat (LE), and carbon, including gross primary production (GPP) and ecosystem respiration (ER). The ER product was estimated according to the short-term temperature response of measured nighttime net ecosystem exchange (NEE) (Reichstein et al., 2005), and GPP as the difference between ER and NEE: i.e., ER − NEE. The gap-filled NEE values (and derived GPP and ER) using the Marginal Distribution Sampling method (Reichstein et al., 2005) were used in this study.

Eddy-covariance and meteorological data from the AmeriFlux L2 data product (version V007, 30-min averages) were used to calculate canopy conductance (G_c, see Sect. 2.7) and atmospheric vapor pressure deficit (VPD). ~~L2 soil water content (SWC) data were also used in the analysis. Missing SWC data from the L2 dataset in the year 2002 were replaced by respective L1 data (version Apr2013).~~ In the analysis, 30-min surface flux data were rejected during periods when the wind direction was in the $[45^{o}: 135^{o}]$ sector (same criterion used by Wharton et al., 2012), as the northeast-to-southeast wind sector is characterized by heterogeneous (age-fragmented) land cover. The data were hourly averaged prior to G_c and VPD calculation. L2 soil water content (SWC) data were also used in the analysis. Missing SWC data from the L2 dataset in the year 2002 were replaced by respective L1 data (version Apr2013).

The AmeriFlux L2 data product (version V007, 30-min averages) was also used to assess the energy balance closure at the site. The energy balance ratio, EBR $= (H + LE)/(R_n - G)$, where R_n is net radiation and G is soil heat flux, was calculated for dry season months (June to September) using 10:00–14:00 PST data and rejecting periods with rain or unfavourable wind direction ($[45^{o}: 135^{o}]$ sector). With the available data, EBR could be calculated for the years of 1998–2001, 2004, and 2006.

Comment [HFD11]: [RC1.12]

2.4 Carbon Isotope Data

Estimated δ^{13}C values of ER (Lai et al., 2005) and observed δ^{13}C values of leaf tissue and soil organic matter (Fessenden and Ehleringer, 2003) at Wind River were used to assess the photosynthetic ^{13}C discrimination in CLM.

Lai et al. (2005) used an automated air sampling system, with inlets at 0.5 m above ground level and at 0.5 canopy height, collecting 15 flasks weekly during the growing season. Most of the flasks (13 out of 15)~~the 15 flasks~~ were dedicated to nighttime sampling (over a single night). The Keeling-plot method was used to infer the weekly $\delta^{13}C_{ER}$ using

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the CO_2 and $\delta^{13}CO_2$ observations (for simplicity, the resulting $\delta^{13}C_{ER}$ values are referred to as "observations" in the text). The monthly averages (June–November) from 2001 to 2003 reported by Lai et al. (2005) were used as reference in the present study.

Fessenden and Ehleringer (2003) conducted measurements of $\delta^{13}C$ of bulk organic tissue from current-year needles of *Tsuga heterophylla* trees and seedlings at the top (55 m), middle (25 m), and bottom (2 m) of the canopy. They also conducted vertical profile measurements of $\delta^{13}C$ of bulk soil organic carbon down to 20-cm depth. The measurements were performed on a 1-month to 2-month time interval. The values reported by Fessenden and Ehleringer (2003) for the growing season in 1999 and 2000 were used as reference.

In the present study, both observed and modeled carbon isotope ratios were expressed as $\delta^{13}\mathrm{C} = \left(\frac{R_x}{R_{std}} - 1\right) \times 1000$ (‰), where R_x is the ^{13}C:^{12}C isotope ratio of the carbon pool/flux of interest and R_{std} is the ^{13}C:^{12}C isotope ratio of a standard reference material (Vienna Pee Dee Belemnite standard).

2.5 CLM Configuration and Simulations

CLM was run at site level using the PTCLM scripting framework (see Kluzek, 2013), as in recent studies (e.g., Mao et al., 2016; Raczka et al., 2016). Land cover was defined as the needleleaf evergreen temperate tree plant functional type. The model was configured to use CLM v.4.5 physics and CLM v.4.5 CN biogeochemistry. The vertical soil carbon profile option was turned on, and the CENTURY Carbon model was selected for the decomposition parameters. The nitrification and de-nitrification sub-model was switched off, as preliminary simulations indicated an excess of nitrogen availability and forest productivity when the respective module was active. Given that the Wind River site is characterized by an old-growth mature forest, no land-cover disturbance was considered in the simulations.

The model was spun-up in a two-stage process, using a pre-industrial component set with a constant, pre-industrial atmospheric CO_2 concentration and $\delta^{13}CO_2$ of 285 ppmv and −6.5‰, respectively. The model was run in accelerated decomposition mode for 600 years (first stage) and then in normal decomposition mode for 1000 years (second and final stage), using the local observed meteorological data (Sect. 2.3) from 1998 to 2006 to drive the model (continuously cycled). Following the spin-up process, a transient run (1850–2006) was performed with prescribed nitrogen deposition, atmospheric CO_2 concentration, and atmospheric $\delta^{13}CO_2$.

The transient atmospheric CO_2 concentrations used in this study were based on the CMIP5 recommendations for annual global mean values (Meinshausen et al., 2011). The transient atmospheric $\delta^{13}CO_2$ values used here were based on ice-core and flask measurements reported by Francey et al. (1999) (annual values in their spline fitting from 1850 to 1981) and flask measurements in Mauna Loa (annual averages from 1981 to 2006) by the Scripps CO_2 program (Keeling et al., 2005), following a similar methodology as in Raczka et al. (2016) (note that, unlike in Raczka et al. (2016), here a seasonal cycle was not superimposed onto the time series). As in the spin-up process, the local observed meteorological data from 1998 to

Comment [HFD12]: [RC2.1.4a]

2006 were cycled during the transient run. The driver-data and model years were aligned in a way to guarantee a perfect match between them during the final 9 years of the simulation (1998–2006).

2.6 CLM Calibration

Initial simulations using the default parameters from CLM resulted in a poor representation of the carbon dynamics at the Wind River site (Figs. A4 and A5). GPP and forest biomass were significantly underestimated. The seasonality of ER was poorly represented and the simulated late-summer GPP was impacted by an underestimation of SWC, resulting~~ed~~ from a poor representation of soil hydrology at the site. Furthermore, the modeled evapotranspiration values were significantly overestimated for the given values of GPP, i.e., the simulated water use efficiency was much lower than the observed. As a result of CLM's poor performance in the simulation of GPP and evapotranspiration, the modeled photosynthetic ^{13}C discrimination was found to be overestimated, reflected on reduced ^{13}C:^{12}C ratios of carbon fluxes and pools.

Comment [HFD13]: [RC2.5]

In order to improve the representation of the carbon dynamics at the site, key model parameters were calibrated as detailed in Appendix A and summarized in Table 1. The adjusted parameters were primarily based on biological measurements at Wind River or at similar stands in the Pacific Northwest. Parameters controlling specific leaf area and stomatal conductance were found to be critical to the simulation of GPP and evapotranspiration and were manually adjusted in a way to minimize the differences between model output and site observations (eddy covariance fluxes). The default soil hydraulic parameters used in CLM version 4.5 were found to be inadequate at Wind River, leading to severe underestimation of SWC and unrealistic soil moisture~~drought~~ stress in the model during late summer. These parameters were reverted back to their default values in CLM version 4.0, with significant improvement in the representation of soil hydrology at the site. In an additional measure to reduce the unrealistic late-summer soil moisture~~drought~~ stress in the model, root distribution was adjusted based on CLM's default parameter values for the broadleaf evergreen temperate tree plant functional type, shifting roots towards deeper soil layers (justified based on physical understanding of the site – see Appendix A8).

Bayesian parameter calibration is a common approach used in modelling studies to account for both the prior parameter distributions and more recent observations. In this case, a Bayesian calibration approach would be complicated by the current lack of prior parameter distributions within CLM in order to create a model ensemble and the computational expense of running a calibration. Commonly used techniques such as Markov Chain Monte Carlo (MCMC) are prohibitively expensive with long CLM simulations, and more advanced techniques for calibration (e.g. using surrogate modeling approaches) are still under development. The simpler approach used here proved to be an effective method to improve model performance at the Wind River AmeriFlux site. The reader is referred to Appendix A for a more complete description of the parameters that were adjusted and the calibration approach used.

Comment [HFD14]: [RC1.1]

All model results presented and discussed in Sects. 3 and 4, unless noted otherwise, are based on the optimized model.

2.7 Canopy Conductance

Observed canopy conductance (G_c, m s^{-1}) was calculated by combining hourly tower data (see Sect. 2.3) with the Penman-Monteith equation (Monteith, 1964) as in Wharton et al. (2012):

$$G_c = \left[\frac{\rho c_p \mathrm{VPD}}{\gamma LE} + \frac{\left(\frac{\Delta_{sat}}{\gamma}\right)\left(\frac{H}{LE}\right)-1}{G_a}\right]^{-1}$$ (13~~7~~)

where ρ and c_p are the density and specific heat of air, respectively (kg m^{-3}, J kg^{-1} K^{-1}), VPD is the atmospheric vapor pressure deficit (kPa), LE is the latent heat flux (W m^{-2}), Δ_{sat} is the slope of the saturation vapor pressure curve as a function of air temperature (kPa K^{-1}), γ is the psychrometric constant (kPa K^{-1}), H is the sensible heat flux (W m^{-2}), and $G_a = u_*^2/U$ is the aerodynamic conductance for momentum transfer (m s^{-1}), where u_* is the friction velocity and U is the wind speed. Atmospheric pressure and air temperature data and the ideal gas law were later used to convert the G_c values to mmol m^{-2} s^{-1}. The calculation of G_c was restricted to daytime hours (10:00–16:00 PST) and to the months of June to September (dry season). Rain events and periods with $LE < 5$ W m^{-2} or relative humidity $> 80\%$ were disregarded. G_c values outside the interval of 0 to 1000 mmol m^{-2} s^{-1} were also disregarded.

For comparison against observations, modeled canopy conductance values were calculated using the same methodology described above, but using hourly CLM output (H, LE, u_*) instead. An alternative would be to calculate canopy conductance directly by upscaling CLM's leaf stomatal conductance and leaf boundary-layer conductance using leaf area index (Eq. 6) ~~(LAI)~~. Canopy conductance values derived from both approaches were found to be strongly correlated. The Penman-Monteith method was ultimately selected for the calculation of G_c in order to allow a more direct comparison between modeled and observed values. This comparison was done as a way to assess the performance of CLM in the simulation of leaf stomatal conductance.

3 Results ~~and Discussion~~

Comment [HFD15]: [RC1.2]

3.1 Carbon Pools and Isotopic Signatures

Comment [HFD16]: [RC1.9]

Figure 2 shows modeled LAI, carbon stocks (leaf, fine root, coarse root, tree wood, and soil organic matter (SOM) carbon), and δ^{13}C of leaf and SOM pools throughout the transient run (1850–2006). Before the transient run, the model was spun-up and successfully equilibrated under the defined pre-industrial scenario, with LAI, carbon stocks, and leaf/SOM carbon isotope ratios reaching steady state (results not shown). The cyclic behavior exhibited in Fig. 2 is related to the driving meteorological data set, which was cycled throughout the simulation period (Sect. 2.5).

From 1850 to 2006, modeled LAI and carbon stocks (Fig. 2a–f) increased due to CO$_2$ fertilization and increasing nitrogen deposition. Average values of LAI, leaf carbon, and tree wood carbon ~~at the end of the simulation (year 2006)~~ were in agreement with the reference values reported in the AmeriFlux database for the Wind River site ~~(Table 2)~~. Modeled fine root and coarse root carbon were underestimated, but within 2 standard deviations from the reference values ~~(Table 2)~~.

The δ^{13}C of leaves and SOM was initialized in the model with a value of −6‰ (default value in CLM, close to the pre-industrial atmospheric $\delta^{13}CO_2$ value of −6.5‰ used in this study). During the model spin-up, in which constant pre-industrial atmospheric $\delta^{13}CO_2$ and CO_2 concentration values were prescribed, the δ^{13}C values stabilized at ≈ −26‰. During the transient simulation~~ (Fig. 2g)~~, the δ^{13}C of both leaves (Fig. 2g) and SOM (Fig. 2h) decreased (the pools became isotopically "lighter"), mostly due to the decreasing atmospheric $\delta^{13}CO_2$ values associated with the "Suess effect" (Keeling, 1979) but also due to the increasing atmospheric CO_2 concentration values. The δ^{13}C of leaves declined faster over the years than the δ^{13}C of SOM, given the fact that leaves have a significantly shorter turnover time than SOM and therefore present a faster response to the changes in atmospheric $\delta^{13}CO_2$ and CO_2 concentration. Modeled δ^{13}C of leaves~~ at the end of the transient simulation~~ compared well against the site observations for top and mid-canopy leaves (−0.8‰ and +0.8‰ difference, respectively), and modeled δ^{13}C of SOM (top 1 m of soil) compared well against site observations for SOM at 20 cm below ground (−0.4‰ difference).~~was within the range of site observations for mid-canopy leaves, and just 0.2‰ below the range of observations for top-canopy leaves (Table 2). Modeled δ^{13}C of SOM (top 1 m of soil) was within the range of site observations for SOM at 20 cm below ground (Table 2).~~

It is important to clarify that CLM has leaf properties that vary continuously with canopy depth, and that two leaf categories (sunlit and shaded leaves) are estimated dynamically on every time step, as a function of canopy structure and solar elevation angle (Thornton and Zimmerman, 2007). The modeled leaf δ^{13}C output corresponds to the isotopic signature of the entire leaf carbon pool, which is calculated from both sunlit and shaded portions of the leaf canopy (see Sect. 2.1). The observed leaf δ^{13}C values in Fig. 2g correspond to measurements at canopy top (55 m), middle (25 m), and bottom (2 m). As pointed out by Fessenden and Ehleringer (2003), the decrease in the observed leaf δ^{13}C values (i.e., increase in photosynthetic ^{13}C discrimination) with canopy depth can be explained by light reduction within the canopy. In principle, the observed mid-canopy values are expected to better represent the isotopic composition of leaves for the whole canopy, in comparison with the observed values at the two canopy extremes, especially given the larger amount of leaf biomass in mid canopy. However, considering how light is reduced within the canopy, the top-canopy δ^{13}C value should still be representative of a significant fraction of the canopy as well, so the whole canopy δ^{13}C is expected to lay somewhere in between the top- and mid-canopy values. As shown in Fig. 2g, the modeled δ^{13}C of the leaf carbon pool was the average between the observed values at canopy top and middle.

Comment [HFD17]: [RC1.10]

The overall agreement between the observed and modeled carbon isotope ratios indicates that ~~the calibrated ~~CLM had skill in simulating the balance between assimilation and stomatal conductance and the associated photosynthetic ^{13}C discrimination. The adjustment of the parameters controlling stomatal conductance in the model (m_{bb} and b_{bb} – see Sect. 2.6, Table 1 and Appendix A9) to improve the simulation of evapotranspiration had a significant impact on the simulation of photosynthetic ^{13}C discrimination. When using the default parameter values (resulting in significantly higher stomatal conductance values), the modeled values of δ^{13}C in leaves and SOM were generally 2–3‰ lower (Fig. A1), departing from site observations~~ (cf. Table 2)~~.

3.2 Energy and Carbon Fluxes

Modeled energy and carbon fluxes are compared against daily-averaged observations in Fig. 3 for the period between 1998 and 2006. “Observed” GPP and ER were obtained from applying a partitioning model to NEE measurements (Sect. 2.3), but are referred to as “observations” in the text.

Modeled LE values were close to observations, with a mean bias error (MBE) of ≈ −3 W m^{-2} and a root mean square error (RMSE) of ≈ 20 W m^{-2}. The adjustment of the stomatal conductance parameters m_{bb} and b_{bb} (Table 1) was fundamental in modifying the LE simulations. When using the default parameter values the modeled evapotranspiration was significantly overestimated, with summer values exceeding observations by almost 100% (Fig. A2a).

In 1998–2003 the model overestimated H (MBE ≈ 32 W m^{-2}, RMSE ≈ 40 W m^{-2}), while in 2004–2006 the modeled values were closer to observations (MBE ≈ 10 W m^{-2}, RMSE ≈ 36 W m^{-2}). The modeled H values did not present significant interannual variability in 1998–2006; however, the observations showed significantly smaller fluxes in 1998–2003 than in 2004–2006. Such changes in the magnitude of H were reported as a potential data issue in the Wind River site documentation available in the AmeriFlux repository.

The overall mean EBR calculated from site observations was 0.88 (see Sect. 2.3 for calculation approach). The energy balance closure for years 2004 and 2006 was high (mean EBR = 1.01 and 1.09, respectively). The model bias of H and LE was relatively small in those years (Figs. 3a, b). In years 1998, 2000 and 2001, mean EBR was significantly lower (0.63, 0.69 and 0.76, respectively). Modeled H presented a relatively large positive bias in those years (Fig. 3a). As discussed above, the observed H values in 1998–2003 were significantly smaller than in 2004–2006, while the LE observations showed approximately the same pattern over the years. The low EBR for years 1998, 2000 and 2001 supports the remark included in the AmeriFlux documentation regarding a potential data issue with H and suggests that the observed values were biased low in 1998–2003. Mean EBR in 1999 was relatively high (0.92), where the reduced H values (Fig. 3a) were compensated by larger LE values (Fig. 3b). In that year, modeled H (LE) had a positive (negative) bias in respect to the observations.

Comment [HFD18]: [RC1.12]

Modeled GPP resembled observed values, with small differences (MBE ≈ 0.23 gC m^{-2} day^{-1}, RMSE ≈ 1.60 gC m^{-2} day^{-1}). Modeled ER exhibited closer correspondence with measurements during the spring and summer months in general (MBE ≈ 0.82 gC m^{-2} day^{-1}, RMSE ≈ 1.85 gC m^{-2} day^{-1}), with summer peaks especially close to measured values. In the colder months, modeled ER was significantly overestimated (MBE ≈ 1.46 gC m^{-2} day^{-1}, RMSE ≈ 1.77 gC m^{-2} day^{-1}).

Despite the significant improvement in the seasonal behavior of ER after the Q_{10} adjustments discussed in Appendix~~Sect.~~ A6, the results indicate that further adjustments also including the base rate of maintenance respiration and the base decomposition rates for each litter and SOM pool within CLM would be necessary to better simulate the observed ER at Wind River. The results suggest that lower base rates and higher Q_{10} values would improve the simulations at the site.

3.3 Isotopic Signatures of GPP and ER

3.3.1 Diurnal Cycle

Modeled $\delta^{13}C_{GPP}$ exhibited a well-defined diurnal cycle (Fig. 4), with minimum values in the early morning and late afternoon and a peak value typically in mid-afternoon, reflecting diurnal changes in the simulated iWUE (see Eqs. 10~~4~~ and 12~~6~~). Modeled $\delta^{13}C$ values of the heterotrophic component of ecosystem respiration (HR) were approximately constant, with a ≈ 0.2‰ change over the entire period of study (1998–2006). On the other hand, modeled $\delta^{13}C$ values of the autotrophic component (AR) were found to be virtually equal to modeled $\delta^{13}C_{GPP}$ during daytime. At nighttime, modeled $\delta^{13}C_{AR}$ was found to change abruptly towards values closer to modeled $\delta^{13}C_{HR}$. Because AR was the major component of the total ecosystem respiration (ER=AR+HR; see Fig. 4a), modeled $\delta^{13}C_{ER}$ exhibited a similar behavior compared to modeled $\delta^{13}C_{AR}$ (Fig. 4b).

In CLM, newly assimilated carbon is first allocated to meet the total maintenance respiration demand of live plant tissues (top priority). When this demand exceeds the supply of carbon via photosynthesis (e.g., during nocturnal periods, wintertime, stress periods), carbon is drawn from a storage pool (excess maintenance respiration pool; CS_{xs}), which is allowed to run a deficit state. The reason CLM allows this deficit state is to avoid the requirement of knowing the size of the total storage pool available to plants and thus the possibility of vegetation dying in a given location if the storage pool is depleted~~, because, without vegetation dynamics active there would not be the possibility of recruiting new vegetation~~. When negative, CS_{xs} is gradually replenished with newly assimilated carbon at a potential rate of $-CS_{xs}/$~~(86400τ_{xs})~~, where τ_{xs} is a time constant (set to 30 days in CLM). The carbon allocation flux to replenish CS_{xs} receives second priority in the model, while the carbon allocation fluxes to support plant growth have third priority. Given this allocation structure, δ^{13}C~~$_{MR}$~~$_{AR}$ ~~(maintenance respiration) is expected to~~will follow $\delta^{13}C_{GPP}$ during daytime (assuming GPP is enough to meet the maintenance respiration~~MR~~ demand), and the $\delta^{13}C$ of the “excess maintenance respiration flux” ($\delta^{13}C_{XSMR}$)~~the CS_{xs} pool~~ during nighttime. CLM does not calculate the isotopic signature of XSMR from CS_{xs}, but from bulk vegetation tissues (total vegetation carbon, TOTVEGC). This is done because CS_{xs} is not a physical quantity, but a construct of CLM. Note that XSMR “borrows” carbon from the CS_{xs} pool, which is allowed to run a deficit state. This “debt” is paid in the future with the replenishment of the CS_{xs} pool with newly assimilated carbon. This construct makes the $\delta^{13}C$ of CS_{xs} non-physical, therefore, the approximation that $\delta^{13}C_{XSMR}=\delta^{13}C_{TOTVEGC}$ is more physically realistic. This approximation makes the nocturnal $\delta^{13}C_{AR}$ to follow $\delta^{13}C_{TOTVEGC}$, explaining the low sensitivity of the nocturnal $\delta^{13}C_{AR}$ to recent ^{13}C discrimination in the results shown in Fig. 4b. ~~Also, the $\delta^{13}C$ of the CS_{xs} pool is expected to have little sensitivity to recent photosynthetic ^{13}C discrimination, given the rate at which the pool is refilled. The simulations results in Fig. 4b align with these expectations.~~

Comment [HFD19]: [RC2.1.4b]

Autotrophic respiration at Wind River is likely fueled by a mixture of stored and recently-fixed carbon, as indicated by ^{14}C measurements from root respiration at the site (Taylor et al., 2015). This process cannot be appropriately modeled by CLM with the current carbon allocation scheme, impacting the simulation of $\delta^{13}C_{ER}$. An explicit representation of carbohydrate storage pools within CLM to support the maintenance respiration demand would improve the simulation of

$\delta^{13}C_{ER}$. The need for a better representation of carbohydrate storage pools within CLM was also highlighted by the $^{13}CO_2$-labeling study conducted by Mao et al. (2016).

It is important to highlight that, unlike models such as SiB (Sellers et al., 1996; Vidale and Stöckli, 2005), CLM does not have a prognostic canopy airspace where $\delta^{13}CO_2$ is impacted by photosynthetic and respiratory fluxes, so the simulation of $\delta^{13}C_{GPP}$ is not affected by the above described limitations in the simulation of $\delta^{13}C_{ER}$.

Comment [HFD20]: [RC2.1.4c]

3.3.2 Seasonal Cycle

~~As illustrated in Fig. 5, m~~Modeled $\delta^{13}C_{GPP}$ exhibited a well-defined seasonal pattern, peaking during the summer as a result of a decrease in the photosynthetic ^{13}C discrimination associated with higher iWUE values (Fig. 5; see also Eqs. 10~~4~~ and 12~~6~~). The summer peak in iWUE was linked to changes in stomatal conductance in response to increased VPD and reduced SWC during the dry summer season~~ associated with summer drought~~.

On a monthly scale, roughly indicated by the smoothed curve in Fig. 5, the modeled $\delta^{13}C_{GPP}$ values presented a similar seasonal pattern in comparison with the $\delta^{13}C_{ER}$ observations at the site by Lai et al. (2005). Differences between $\delta^{13}C_{GPP}$ and $\delta^{13}C_{ER}$ are obviously expected, as $\delta^{13}C_{ER}$ depends on the contribution of recently-assimilated carbon to AR, the AR:ER ratio, and also post-photosynthetic fractionation (Bowling et al., 2008; Brüggemann et al., 2011). The seasonal pattern in the observed $\delta^{13}C_{ER}$ (Fig. 5) could be partially attributed to an eventual spring-to-summer decrease in AR:ER ratio (assuming $\delta^{13}C_{HR} > \delta^{13}C_{AR}$). ^{14}C measurements from below-ground respiration components at Wind River reported by Taylor et al. (2015) do indicate a spring-to-summer decrease in the contribution of root respiration (RR) towards total soil respiration (SR=RR+HR). The similarity of the seasonal patterns of observed $\delta^{13}C_{ER}$ and modeled $\delta^{13}C_{GPP}$ suggests that stomatal response to water stress~~drought~~ could also be driving the seasonal pattern in the observed $\delta^{13}C_{ER}$ at the site. The broader implication is that $\delta^{13}C_{ER}$, which can be more easily measured than $\delta^{13}C_{GPP}$, can be reasonably used as a surrogate to indicate forest response to water stress~~drought~~ at Wind River.

Due to the limitations in the carbon allocation scheme used in CLM (Sect. 3.3.1), the simulated $\delta^{13}C_{ER}$ values were found to be inconsistent with the site observations, with nocturnal values approximately constant throughout the entire period of study (1998–2006), exhibiting little sensitivity to recent photosynthetic ^{13}C discrimination. Diurnal values, on the other hand, were found to be strongly correlated with $\delta^{13}C_{GPP}$, given the fact that in CLM current photosynthate directly fuels AR (results not shown).

The adjustment of the stomatal conductance parameters m_{bb} and b_{bb} to improve the simulation of evapotranspiration (Sect. 2.6, Table 1 and Appendix A9) led to a significant change in the simulation of $\delta^{13}C_{GPP}$. When the default parameter values were used, modeled $\delta^{13}C_{GPP}$ was generally 2–3‰ lower due to higher photosynthetic ^{13}C discrimination (Fig. A2b), also presenting a considerable reduction in the amplitude of the seasonal cycle. The difference between modeled $\delta^{13}C_{GPP}$ and observed $\delta^{13}C_{ER}$ was significantly larger. As discussed in Sect. 3.1, site observations of leaf and SOM $\delta^{13}C$ support the notion that the default stomatal conductance parameters are inadequate at Wind River, resulting in excessive photosynthetic ^{13}C discrimination.

~~Thanks to the recent implementation of photosynthetic ^{13}C discrimination within CLM, the results of the present study indicate that δ^{13}C data can be used to constrain stomatal conductance and iWUE in the model as an alternative to eddy covariance flux measurements. This new capability in CLM also opens an interesting opportunity for future model developments, as isotopes expose a conceptual weakness in CLM's carbon allocation scheme (the deficit-based accounting scheme described in Sect. 3.3.1). In future efforts, δ^{13}C$_{ER}$ data can be used to guide a restructuring of the model, moving away from the deficit-based accounting scheme towards an explicit representation of carbohydrate storage pools.~~

3.4 Ecosystem ~~Drought~~ Response to Water Stress

Overall, CLM was able to reasonably capture the observed interannual variability of GPP at the study site (Fig. 3c). The behavior of observed GPP in 2002 and 2006 stands out, showing an early-season peak followed by a quick reduction, suggesting strong water stress in those years, especially in 2002. Among the years studied here, 2002 and 2006 had the lowest summer precipitation. Spring precipitation was also low in 2006 but normal in 2002. Observed canopy conductance during the spring and summer of 2006 was smaller than in 2002, but a stronger attenuation of GPP was observed in 2002, suggesting that water stress was not the main reason for the attenuated GPP values in 2002. CLM was able to simulate the observed GPP behavior in 2006 but not in 2002. The reason for the model-data mismatch in the spring/summer of 2002 is currently unclear. Despite the fact that meteorological forcing data from 1998–2006 were continuously cycled throughout the transient run (1850–2006), meaning that the impact of any slow secular change in the forcing data was not captured in the simulation, the simulated GPP still compared reasonably well against observations.

Comment [HFD21]: [RC2.1.1]

Throughout the simulation period (1998–2006), ~~the calibrated~~ CLM predicted a few periods where the ecosystem was under the influence of soil moisture~~drought~~ stress (Fig. 6). As indicated by the β_t parameter (Eq. 3), which varies from 0 (maximum soil moisture~~drought~~ stress) to 1 (no soil moisture~~drought~~ stress) (see Sect. 2.1), those periods included the summers of 1998, 2006, 2003, and 2002, in decreasing order of stress intensity~~drought severity~~. The departures from $\beta_t = 1$ typically occurred when modeled SWC (top 5 soil layers, 0–27 cm) decreased below ≈ 20%. Note that, at Wind River, SWC at permanent wilting point and at field capacity is 14% and 30%, respectively (Wharton et al., 2009).

Comment [HFD22]: [RC2.9]

~~After~~ With the adjustment of soil hydraulic~~ology~~ parameters (Appendix~~Sect.~~ A7), CLM was able to adequately simulate SWC throughout most of the years within the study period (Fig. 6), especially during the summer months, with an overall summer MBE of 3.24%. However, the simulated SWC significantly departed from observations in 1999–2002. CLM, which was driven by observed precipitation at the site, indicated higher SWC than observations in 1999–2002, particularly during the summer months, with a summer MBE of 8.05%. For the remaining years, summer MBE was −0.27%. The SWC observations starting on the second year of the site records (1999) up to the data gap in 2002 presented a different pattern in comparison with the remaining years, showing an apparent negative offset of near 10%. It is likely that the apparent shift in the time series of observed SWC was instrument-related. In 1999–2002, soil moisture monitoring at the site consisted of 2, 2-pronged TDR probes instead of 6, 3-pronged TDR probes, likely resulting in less-accurate data collection.

Observed canopy conductance was found to be strongly dependent on VPD, following a decreasing exponential relationship (Fig. 7). In order to investigate the additional dependence on soil moisture~~drought~~ stress, the data points were divided into 4 bins according to the observed values of SWC (Fig. 7a). The linear regression fit between $\log G_c$ and VPD for the points corresponding to the lowest SWC bin (SWC<17.5%, ≈ 22% of all data points) was virtually the same as the linear regression considering all data points. If the forest were under soil moisture~~drought~~ stress at those low SWC levels, the former regression curve with data points from the lowest SWC bin would be expected to be found below the latter. Instead, the SWC<17.5% regression curve was very similar—even slightly above the regression curve using all data points.

The lack of sensitivity of observed G_c to observed SWC (Fig. 7a) was likely associated with a negative bias in SWC in 1999–2002. Observed G_c was found to respond to modeled SWC (driven by observed precipitation) (Fig. 7b). As discussed above, the observed SWC values in 1999–2002 were suspected to have a negative bias, i.e., drier than reality. G_c values in Fig. 7a corresponding to the summer of 1999–2002 were tagged as belonging to the lowest SWC bin, but in reality, they could be associated with wetter, non-moisture~~drought-~~ stress conditions. Assuming CLM's summer simulated SWC (driven by observed precipitation) was not as biased as the observed SWC might be, we instead used the modeled SWC values to probe the G_c vs. VPD relationship under different SWC regimes in Fig. 7b. Interestingly, with this approach, a distinct pattern emerged for the data points within the lowest SWC bin. The regression curve considering all data points was $\log G_c = -0.59\mathrm{VPD} + 6.06$ ($r = -0.60$) and when considering only the data points from the lowest bin (modeled SWC<21.25%, ≈ 24 % of all points), the regression curve was $\log G_c = -0.50\mathrm{VPD} + 5.71$ ($r = -0.56$). The latter regression curve corresponded to reasonably lower G_c values, especially at low VPD levels, which is compatible with a moisture~~drought~~ stress scenario. The result supports the suspicion of a negative bias in the observed SWC data in 1999–2002.

Similar to observations, modeled canopy conductance was also found to be strongly dependent on VPD (Fig. 8). This is expected given the Ball-Berry stomatal conductance model used in CLM (Eq. 2). The Ball-Berry model has a direct dependence on leaf relative humidity (leaf RH), not leaf VPD, but these variables are strongly correlated. The correlation between modeled G_c and RH was found to be slightly higher than between modeled G_c and VPD, while observed G_c correlated slightly better with VPD than RH (results not shown). The results indicate that a direct dependence on leaf VPD in CLM's stomatal conductance model, rather than leaf RH, would lead to a more accurate representation of stomatal functioning at Wind River, but overall, for the period analyzed in the present study, such improvement is expected to be small. The general dependence of modeled canopy conductance on VPD was very similar in comparison with observations, as indicated by the linear regression curve between $\log G_c$ and VPD in Fig. 8 using all data points ($\log G_c = -0.59\mathrm{VPD} + 6.04$; compare with $\log G_c = -0.59\mathrm{VPD} + 6.06$ in Fig. 7b). The correlation between observed $\log G_c$ and VPD, however, was lower than for the model results ($r = -0.60$ and $r = -0.91$, respectively).

Comment [HFD23]: [RC1.15]

The impact of soil moisture stress on G_c was reasonably captured in CLM (Fig. 8b; cf. Fig. 7b). The impact of soil moisture~~drought~~ stress on modeled G_c is clearly visible in Fig. 8a, in which the data points were binned according to β_t.

With increasing soil moisture~~drought~~ stress (decreasing β_t values), the modeled G_c values still maintained a strong dependence on VPD, but were shifted downward, particularly at low VPD levels. In order to allow a more direct comparison against Fig. 7b, ~~between the impact of drought stress on modeled and observed canopy conductance,~~ the data points were binned~~separated~~ according to modeled SWC in Fig. 8b. The points in the lowest SWC bin (SWC<21.25%, ≈ 22% of all points) roughly corresponded to the periods under soil moisture~~drought~~ stress ($\beta_t < 1$). The regression curve for the SWC<21.25% group laid reasonably below the regression curve considering all data points ($\log G_c = -0.53\mathrm{VPD} + 5.80$, $r = -0.90$ and $\log G_c = -0.59\mathrm{VPD} + 6.04$, $r = -0.91$, respectively). The regression curves associated with SWC<21.25% were similar for the observed and modeled results (Figs. 7b and 8b), indicating that CLM could reasonably simulate soil moisture stress at Wind River, although with a small underestimation~~but apparently indicated a small underestimation of drought stress in CLM~~ (i.e., a small overestimation of G_c; note the G_c intercepts at 301 and 331 mmol m^{-2} s^{-1} in Figs. 7b and 8b, respectively). It is important to point out, however, that modeled SWC was used to segregate the observations in Fig. 7b due to the potential bias in the SWC observations discussed above.

Modeled δ^{13}C$_{\mathrm{GPP}}$ and G_c were highly correlated ($r = -0.88$, $p < 0.001$; Fig. 9b). Modeled G_c generally decreased into the summer season, leading to an increase in water use efficiency and a decrease in photosynthetic ^{13}C discrimination, resulting in higher δ^{13}C$_{\mathrm{GPP}}$ values. Observed δ^{13}C$_{\mathrm{ER}}$ was found to have a low negative correlation with observed G_c, but not statistically significant ($r = -0.27$, $p = 0.396$; Fig. 9a). The low correlation was likely a result of δ^{13}C$_{\mathrm{ER}}$ reflecting constraints of prior environmental drivers in comparison with the more rapid response of G_c to more recent environmental drivers. Another possible explanation is that the monthly δ^{13}C$_{\mathrm{ER}}$ values in Fig. 9a were obtained by averaging up to 4 discrete weekly observations (see Sect. 2.4), in contrast with the calculation of monthly G_c, which used daytime values for each day of the month. It is important to mention that the observed δ^{13}C$_{\mathrm{ER}}$ ~~do~~ show a clear seasonal pattern (Fig. 5), with values peaking during summer likely in response to changes in g_s and iWUE associated with increasing water stress ~~summer drought~~ (see discussion in Sect. 3.3.2), but the present results indicate a lag in this response.

4 Discussion

Comment [HFD24]: [RC1.2]

4.1 Ecosystem Response to Water Stress

Comment [HFD25]: [RC2.1.1]

We found that the major cause of water stress leading to stomatal response at Wind River during summer was the elevated VPD, and not the reduced soil moisture (Section 3.4). Observed canopy conductance values at the site strongly decreased at moderate VPD levels, regardless of soil moisture conditions (Fig. 7b). The high sensitivity of stomatal response to changes in VPD was also shown and discussed in Wharton et al. (2009). As pointed out in their study, “even under moderate VPD levels, foliage at the tops of tall evergreen conifer trees often reach near critical values for cavitation due to a long path distance between the water table and the hydraulic capacity of the xylem, and as a result shut their stomata frequently (Ryan and Yoder 1997)". They also point out that soil moisture depletion is usually not limiting at the site because the mature trees are capable to tap water from deeper soil layers. This is generally consistent with our findings (Sect. 3.4), however, we also found that stomatal conductance responded to soil moisture stress during periods of more severe SWC depletion and low VPD (Fig. 7b).

Overall, CLM was able to simulate the observed response of canopy conductance to VPD and SWC, reasonably capturing the impact of water stress on ecosystem functioning (Fig. 8). Similarly to observations, VPD exerted a strong limitation on modeled G_c, while SWC was usually not limiting. Note that β_t was equal to 1 (no soil moisture stress) throughout most of the period of study (Fig. 6), in alignment with the explanation by Wharton et al. (2009) that the mature trees at the site are capable to access water from deeper soil layers. Note also that the default NETT PFT root distribution in CLM was shifted towards deeper soil layers (Appendix A8), aiming to improve the simulation of β_t. Despite the good overall model-data agreement (G_c dependency on VPD and SWC) after calibration, the results indicate a small underestimation of soil moisture stress in CLM, as discussed in Sect. 3.4. Calibration of the parameters controlling the plant wilting factor (Eq. 5) and additional calibration of the root distribution parameters could improve the results but are out of scope here.

An obvious but important point that must be highlighted is that in order to adequately simulate soil moisture stress, CLM must first adequately simulate SWC. Even when the model is driven by observed precipitation data (the case of the present study), this task is not trivial. As discussed in Appendix A7, CLM's hydrology submodel performed poorly at Wind River when the default soil hydraulic parameters were used, leading to a strong dry bias in SWC. The original parameters used in the previous version of CLM (Version 4.0) were found to perform much better at the site, likely due to a reduction of subsurface runoff and consequent increase in water retention in the soil column. As the default parameter values are intended for global simulations, it is natural to expect site-to-site variation in model performance (see Sect. 4.2). Raczka et al. (2016), for instance, did not find issues with the default soil hydraulic parameters in their CLM 4.5 simulation at the Niwot Ridge AmeriFlux site. This difference in impact between the sites may have resulted from unique soil properties or differences in precipitation and evaporative demand between the sites during the summer.

As pointed out in Sect. 3.4, the results of the present study indicate that a direct dependence on leaf VPD in CLM's stomatal conductance model, rather than leaf RH, would lead to a more accurate representation of stomatal functioning at Wind River, but overall, for the period analyzed in the present study, such improvement is expected to be small. It is important to emphasize that this expectation refers to the results presented here only. In case of model predictions under future climate scenarios, in which atmospheric VPD is predicted to change while RH stays the same (as discussed in Sato et al., 2015), a direct dependence on leaf VPD in the stomatal conductance model becomes critical. The next CLM release (Version 5) is expected to replace the Ball-Berry model with the Medlyn model (Medlyn et al., 2011), which directly depends on leaf VPD. This modification is expected to be more relevant for climate change simulations. Note that the present analysis is based on a hindcast simulation using a stable climate.

Comment [HFD26]: [RC1.15]

4.2 Calibration of CLM

Comment [HFD27]: [RC2.1.2]

Substantial calibration of model parameters was necessary to simulate the observed energy and carbon dynamics at Wind River, an old-growth (~500-years-old) coniferous forest site dominated by Douglas-fir and western hemlock trees and characterized by Mediterranean climate. This is not surprising given that the default parameters used in CLM are intended for global simulations, so model performance at particular sites is expected to vary greatly, requiring site-specific calibration in order to adequately simulate the observations. This is also demonstrated in the studies by Raczka et al. (2016) and Mao et al. (2016). Raczka et al. (2016) investigated the performance of CLM at the Niwot Ridge AmeriFlux site, a ~110-years-old subalpine coniferous forest site in Colorado, USA, consisting of lodgepole pine, Engelmann spruce, and subalpine fir, while Mao et al. (2016) evaluated CLM in a 10-year-old loblolly pine stand in Tennessee, USA. In both cases significant site-specific specification and calibration of model parameters were also necessary. Note that these sites fall into the same PFT category as Wind River (NETT PFT). Despite the significant differences between the 3 sites, the results presented here and in Raczka et al. (2016) and Mao et al. (2016) converge in respect to the calibration of the Ball-Berry stomatal conductance slope, m_{bb}. It is promising that despite the range in stand age and climate conditions amongst these sites, there appears to be a consensus that reduced stomatal conductance is required across all sites. This bodes well when upscaling to regional simulations.

A reduction of m_{bb} from 9 (default) to 6 was necessary to simulate the observed GPP, LE, and δ^{13}C values (leaf, SOM) at Wind River. This aligns with the results by Mao et al. (2016), as they were able to simulate the observations at their Tennessee site, including biomass δ^{13}C values, with an optimized m_{bb} of 5.6. However, as discussed in Appendix A9, the present results show that the significant reduction of m_{bb} from 9 to 6 may represent a tradeoff with model representation of nitrogen limitation. When using CLM's default nitrogen limitation scheme and m_{bb} value, Raczka et al. (2016) found significant overestimation of ^{13}C discrimination at Niwot Ridge due to excessive stomatal conductance, similarly to the present study. When using an alternative nitrogen limitation scheme based on V_{cmax25} down-regulation, maintaining the coupling between net leaf assimilation and g_s, Raczka et al. (2016) found significant improvement in the simulations. This alternative scheme was also tested here while keeping the default m_{bb} value, and the results were similar compared to the model run with default nitrogen limitation scheme and $m_{bb} = 6$ (Appendix A9).

The results in the present study indicate that it is possible to account for the partial coupling between net leaf assimilation and stomatal conductance in CLM through the adjustment of m_{bb} to achieve reasonable carbon and energy exchange behavior, including ^{13}C discrimination. This is also supported by the results in Mao et al. (2016). A more detailed evaluation of model skill in simulating ^{13}C discrimination with this approach, in comparison with the V_{cmax25} down-regulation approach (fully-coupled CLM), would depend on high-frequency observations of $\delta^{13}C_{GPP}$ as in Raczka et al. (2016). These data were not available at Wind River. Note that ^{13}C discrimination at Wind River was inferred from δ^{13}C measurements of leaves and soil organic matter.

The results in Raczka et al. (2016), Mao et al. (2016), and in the present study indicate that $m_{bb} = 9$ is "excessive" when the default nitrogen limitation implementation is used in the simulations, with the latter two studies indicating that $m_{bb} \approx 6$ is a more appropriate value to simulate the site observations. This agreement at 3 very distinct sites is encouraging and suggests that CLM could possibly benefit from a revised m_{bb} value of 6 for the NETT PFT, keeping in mind that such adjustment to improve model skill would also account for structural error. At the same time, the results presented here and in Raczka et al. (2016) indicate that the default $m_{bb} = 9$ is reasonable for simulations when the V_{cmax25} down-regulation scheme is implemented in the model, although Raczka et al. (2016) still found a small overestimation of ^{13}C discrimination at Niwot Ridge suggesting that a smaller m_{bb} value would better simulate the site dynamics. It is important to point out, however, that the experimental literature indicates generally lower m_{bb} values for coniferous forests (see for example the survey by Williams et al., 2004, Table 6.3, and Miner et al., 2017, Fig. 1). The Simple Biosphere Model (Sellers et al., 1996), for instance, uses $m_{bb} = 6$ for conifers and $m_{bb} = 9$ for other C_3 plants, while CLM uses $m_{bb} = 9$ for all C_3 plants. Further investigation of the applicability of the revised m_{bb} value (or the current default value while using the V_{cmax25} down-regulation scheme as in Raczka et al., 2016) at other NETT PFT sites is recommended for future studies.

4.3 Recommendations for Structural Improvement within CLM

Comment [HFD28]: [RC2.1.2]

The results of the present study demonstrates that δ^{13}C observations can be used to constrain stomatal conductance and iWUE in CLM as an alternative to eddy covariance flux measurements, leveraging the recent implementation of photosynthetic ^{13}C discrimination within the model. The adjustments made on the parameters controlling stomatal conductance within the model, originally aiming to improve the simulation of evapotranspiration, were critical to simulate the observed photosynthetic ^{13}C discrimination at Wind River, inferred from δ^{13}C measurements of leaves and soil organic matter. As discussed in Sect. 4.2, these adjustments to improve model skill interacted strongly with the nitrogen limitation scheme. A possible interpretation of results from this and other recent studies is that growth limitation due to restricted nitrogen availability does not operate instantaneously upon photosynthesis (e.g., through nitrogen downscaling in the default version of CLM 4.5) but is accounted for further "downstream" during the allocation of carbon.

For example, Metcalfe et al. (2017) proposed a revised model structure in which GPP is not instantaneously down-regulated during photosynthesis, but the excess photosynthate, which cannot be allocated to structural pools due to insufficient nitrogen supply, is allocated to a new nonstructural carbohydrate storage pool within the model. Carbon from this pool is able to return to the atmosphere via the inclusion of a single additional respiration term within the model. This new model structure provides a solution for the issue regarding the partial coupling between net leaf assimilation and stomatal conductance. Alternatively, a foliar nitrogen model could be used to account for nitrogen limitation directly within the estimation of photosynthetic capacity (Ghimire et al., 2016), removing the requirement for nitrogen downscaling. A similar approach is planned to be included in the next release of CLM (version 5.0).

The use of δ^{13}C$_{ER}$ observations as a strong constraint upon CLM is hindered by the lack of an explicit representation of carbohydrate storage pools within the model to support autotrophic respiration (Fig. 4). The results from the ^{13}C-labeling study by Mao et al. (2016) also illustrate the issue and highlight the need of structural improvements in CLM's carbon allocation scheme. One implication of this issue is that it prevents a more direct use of $\delta^{13}C_{ER}$ observations —which are easier to obtain and more frequently available than $\delta^{13}C_{GPP}$ observations— for evaluation of ^{13}C discrimination in CLM. It may also limit the applicability of CLM for global atmospheric ^{13}C budget studies focusing on land-ocean flux partitioning (e.g., van der Velde et al., 2013), as errors in the simulation of the land isotopic disequilibrium ($\delta^{13}C_{ER} - \delta^{13}C_{GPP}$) can propagate to the estimation of the land-ocean partitioning and the estimation of variability of each sink (van der Velde et al., 2014). Van der Velde et al. (2014) were able to reasonably simulate mean observed $\delta^{13}C_{ER}$ values for a selection of sites from the Biosphere-Atmosphere Stable Isotope Network (BASIN; Pataki et al., 2003) using a modified version of the SiB-CASA model including representation of ^{13}C isotopes and modified carbon storage pools. The original SiB-CASA model (Schaefer et al., 2008) has a single storage pool representing sugars and starch, with only the sugar portion being readily available for plant growth and maintenance. The effective pool turnover rate in this configuration is ~70 days. In the modified model, sugar and starch allocation are simulated separately with 2 distinct pools, with prescribed turnover rates of 7 days (sugar to starch) and 63 days (starch to sugar). Van der Velde et al. (2014) found significant improvement in the simulation of $\delta^{13}C_{ER}$ with the new carbon allocation approach. We recommend that CLM adopt a similar carbon allocation scheme, moving away from the deficit-based accounting scheme (Sect. 3.3.1) towards an explicit representation of carbohydrate storage pools such as in the SiB-CASA model (van der Velde et al., 2014).

Another shortcoming in CLM is the fact that mesophyll conductance (g_m) is not simulated, i.e., intracellular and intercellular CO_2 are assumed to be equal. As demonstrated here and in Raczka et al. (2016) and Mao et al. (2016), CLM is able to reasonably simulate ^{13}C discrimination by either adjusting the stomatal conductance slope parameter or using an alternative nitrogen limitation scheme (V_{cmax25} down-regulation), but the impact of not including g_m in the simulations must be investigated. Mesophyll conductance was recently incorporated in CLM by Sun et al. (2014), however it still has to be linked to the carbon isotope submodel. This is another front where ^{13}C observations can be used for model evaluation and development.

Comment [HFD29]: [RC1.5]

5~~4~~ Conclusions

Comment [HFD30]: [RC1.2]

After ~~a~~ substantial calibration of model parameters, CLM was able to simulate energy and carbon fluxes, leaf area index, and carbon stocks at an old-growth coniferous forest (Wind River AmeriFlux site) in general agreement with site observations. Overall, the calibrated CLM was able to simulate the observed response of canopy conductance to atmospheric vapor pressure deficit and soil water content, reasonably capturing the impact of water~~drought~~ stress on ecosystem functioning. Key model adjustments to simulate observed flux and carbon stock patterns included 1~~i~~) parameters controlling the variation of specific leaf area through the forest canopy (SLA_0, m), with significant impact on GPP, 2~~ii~~) parameters controlling stomatal conductance (m_{bb}, b_{bb}), with significant impact on the simulated latent heat flux and water use efficiency, and 3~~iii~~) soil hydraulic parameters, with impact on soil water content and on the soil moisture~~drought~~ stress parameter, β_t. ~~The calibrated parameters presented here may be of use for future modeling studies involving stands of similar age and composition under a similar climate regime. More broadly, the calibration of the Ball-Berry stomatal conductance parameters aligned with observations reported in the literature for coniferous trees, suggesting that a future release of CLM would benefit from using a distinct, lower slope value ($m_{bb} = 6$) for conifers, rather than a unique value for all C3 plants ($m_{bb} = 9$).~~

The calibrated CLM was able to simulate carbon isotope ratios of leaves and soil organic matter at Wind River, in general agreement with site observations. The adjustments made on the parameters controlling stomatal conductance within the model, originally aiming to improve the simulation of evapotranspiration, were critical to simulate the observed photosynthetic ^{13}C discrimination at the site, inferred from δ^{13}C measurements of leaves and soil organic matter. This demonstrates that stable carbon isotopes can serve as an alternative to eddy covariance flux measurements for constraining stomatal conductance. The simulation of nocturnal δ^{13}C$_{ER}$ was found to be inconsistent with site observations, with results showing little sensitivity to recent photosynthetic ^{13}C discrimination. The inclusion of explicit carbohydrate storage pools within CLM (and removal of the current deficit-based carbon accounting system) to support the maintenance respiration demand from live plant tissues would improve the simulation of δ^{13}C$_{ER}$. ~~The optimized model also tended to overestimate ecosystem respiration through the winter, suggesting further investigation of the respiration-temperature relationships and perhaps also changes in physiological activity of leaves and fine roots through the winter.~~

We found an optimized stomatal slope value ($m_{bb} = 6$) was necessary at Wind River, consistent with previous CLM experiments from distinct needleleaf evergreen temperate forest sites. This suggests that this parameterization could apply to broader scale simulations of this PFT. We also found a tradeoff between adjustment of stomatal slope and changes to the nitrogen limitation scheme. The best long term solution may be to replace this nitrogen scheme with alternative approaches.

The hydrology submodel within CLM and its parameterization deserve special attention because the simulation of soil water content has a direct impact on β_t, and thus on stomatal conductance. Wind River required a unique calibration to achieve reasonable soil moisture, that was not consistent across other sites. This suggests that simulation of soil moisture in regional studies should be used with caution.

The recent inclusion of the photosynthetic ^{13}C discrimination functionality in CLM opens a new opportunity for model testing and development. ~~The results presented here indicate that δ^{13}C data can be used to constrain stomatal conductance and iWUE in the model, as an alternative to eddy covariance flux measurements.~~ The results presented here demonstrate that carbon isotopes can expose structural weaknesses in the model, such as the deficit-based accounting system in CLM's carbon allocation scheme and the partial coupling between net leaf photosynthesis and stomatal conductance caused by the nitrogen limitation scheme. δ^{13}C observations provide a key constraint that may guide future CLM development. ~~Also, this new functionality in CLM opens an interesting opportunity for future model developments, as~~

~~isotopes expose a conceptual weakness in CLM's carbon allocation scheme (the deficit-based accounting system). In future efforts, $\delta^{13}C_{ER}$ data can be used to guide a restructuring of the model, moving away from the deficit based accounting scheme towards an explicit representation of carbohydrate storage pools.~~

Appendix A: CLM Calibration

Most of the adjustments were performed on parameters particular to the needleleaf evergreen temperate tree plant functional type in CLM. For brevity, this plant functional type is referred to as NETT PFT in the following Sections.

A1 Carbon Allocation Ratios

By default, CLM uses a dynamic new-stem-carbon-to-new-leaf-carbon allocation ratio ($A_{s:l}$, gC gC^{-1}) for the NETT PFT, which rises with increasing net primary production. A survey by White et al. (2000) indicates an average $A_{s:l}$ of 2.2 ± 0.89 gC gC^{-1} for needleleaf evergreen forests. Measurements reported by Hudiburg et al. (2013) for a region close to the Wind River site and characterized by forests of similar species composition vary approximately between 1 and 3.5 gC gC^{-1} (their Fig. A1 – Mesic sites). A fixed value of $A_{s:l} = 2$ gC gC^{-1} (value also used by Thornton et al., 2002 in their BIOME-BGC simulations for the Wind River site) was found to improve the simulated forest biomass and was adopted in this study for the NETT PFT.

The new-fine-root-carbon-to-new-leaf-carbon allocation ratio parameter ($A_{fr:l}$, gC gC^{-1}) for the NETT PFT was also changed based on observations at the Wind River site reported in the AmeriFlux database indicating $A_{fr:l} = 0.385$ gC gC^{-1} rather than the default value of 1 gC gC^{-1}. The change meant a significantly greater carbon investment to leaves, helping to increase the modeled GPP towards the site observations.

A2 Carbon:Nitrogen Ratios

Leaf-litter C:N ratio (CN_{llit}, gC gN^{-1}) for the NETT PFT was adjusted based on measurements at the Wind River site (Klopatek, 2007) to 76.4 gC gN^{-1} (mean observed value). Based on the mean observed CN_{llit} and assuming a nitrogen retranslocation efficiency of 50% (survey by Parkinson, 1983 indicates efficiencies around 50% for conifer trees and 36–69% for Douglas-fir in particular), the leaf C:N ratio (CN_l, gC gN^{-1}) for NETT PFT was adjusted to 38.2 gC gN^{-1}. The updated parameters differ little from the default values ($CN_{llit} = 70$ gC gN^{-1}, $CN_l = 35$ gC gN^{-1}).

Fine-root C:N ratio (CN_{fr}, gC gN^{-1}) for the NETT PFT was also adjusted based on measurements at the Wind River site (Klopatek, 2007). The value was adjusted from 42 gC gN^{-1} (default) to 64.7 gC gN^{-1} (mean observed value), meaning a significantly smaller nitrogen investment in fine roots resulting in more nitrogen for investment in leaves. This change helped to increase the modeled GPP towards the site observations.

A3 Leaf Longevity

Measurements reported by Hudiburg et al. (2013) for a region near the Wind River site and characterized by forests of similar species composition indicate leaf longevity (τ_l) of 5 yrs. This value was adopted for the NETT PFT, replacing the default value of 3 yrs. This change contributed particularly to an increase in the modeled leaf area index.

A4 Specific Leaf Area

In CLM, specific leaf area (SLA, m^2 leaf gC^{-1}) is assumed to be linear with canopy depth x (expressed as overlying leaf area index, m^2 leaf m^{-2} ground) (Thornton and Zimmermann, 2007):

$$\mathrm{SLA}(x) = \mathrm{SLA}_0 + mx \qquad \text{(A1)}$$

where SLA$_0$ is the specific leaf area at the top of canopy and m is a linear coefficient (m^2 ground gC^{-1}). Integrating this equation over the canopy, a relationship can be established where leaf area index (LAI, m^2 leaf m^{-2} ground) is calculated as a function of leaf carbon (C_l, gC m^{-2} ground), knowing the parameters SLA$_0$ and m (Thornton and Zimmermann, 2007):

$$\mathrm{LAI} = \frac{\mathrm{SLA}_0(e^{mC_l}-1)}{m} \qquad \text{(A2)}$$

The default NETT PFT values in CLM for SLA$_0$ and m are 0.01 m^2 leaf gC^{-1} and 0.00125 m^2 ground gC^{-1}, respectively. These values were found to be too large for the Wind River site. Using them in Eq. (A2) with a C_l of 941 gC m^{-2} ground (mean observation at the Wind River site reported in the AmeriFlux database) results in an LAI of ≈ 18 m^2 leaf m^{-2} ground, instead of ≈ 9 m^2 leaf m^{-2} ground according to the observations at the Wind River site (AmeriFlux database).

In CLM, the maximum rate of carboxylation at 25°C (V_{cmax25}) is proportional to the area-based leaf nitrogen concentration defined as $N_a = 1/(CN_l\mathrm{SLA}_0)$, i.e., $V_{cmax25} \propto 1/\mathrm{SLA}_0$. Using the default NETT PFT values for SLA$_0$ and m led to the development of large and thin leaves with reduced N_a and V_{cmax25}, resulting in excessive LAI and significant down-regulation of GPP. Smaller SLA$_0$ values were attempted (manual trial and error), with m values constrained by Eq. (A2), the SLA$_0$ value, and the site observations of LAI and C_l mentioned above, aiming to minimize model errors in the simulation of GPP and LAI. $\mathrm{SLA}_0 = 0.006$ m^2 leaf gC^{-1} and $m = 0.000985$ m^2 ground gC^{-1} were found to significantly improve the simulations and were adopted instead of the default values. Measurements reported by Woodruff et al. (2004) indicate that the ratio of leaf dry mass to leaf area reaches 263 g m^{-2} leaf near the canopy top at Wind River (their Fig. 6). Assuming the mass of carbon is 50% of the dry mass, the observed value corresponds to 131.5 gC m^{-2} leaf, i.e., an SLA$_0$ value of 0.0076 m^2 leaf gC^{-1}, indicating that the optimized SLA$_0$ value moved in the right direction from the default NETT PFT value (0.0100 down to 0.0060 m^2 leaf gC^{-1}), but ended up slightly lower than the observed value.

Comment [HFD31]: [RC1.8]

A5 Tree Mortality

Results reported by van Mantgem et al. (2009) indicate an increasing trend of plant mortality rates (M, yr^{-1}) for Pacific Northwest forests, with M growing from ≈ 1% yr^{-1} in 2000 towards ≈ 1.5% yr^{-1} in 2010. In CLM, a default rate of $M = 2\%$ yr^{-1} is used for all vegetation types, which was found to be excessive at Wind River, leading to a reduced modeled forest biomass. $M = 1.5\%$ yr^{-1} was found to yield results closer to site observations and was therefore adopted in this study.

A6 Temperature Sensitivity Coefficient (Q_{10})

The effect of temperature on maintenance respiration (component of autotrophic respiration) in CLM is calculated via a Q_{10} formulation, where the base rate of maintenance respiration is multiplied by $Q_{10}^{(T_a - T_{ref})/10}$, where Q_{10} is a temperature sensitivity coefficient, T_a is air temperature, and T_{ref} is a reference temperature. For the maintenance respiration cost for live fine roots, soil temperature at the respective soil layer ($T_{s,i}$) is used instead of T_a. Similarly, the effect of temperature on decomposition (and therefore on heterotrophic respiration) is also calculated via a Q_{10} formulation, where the base rates of decomposition are multiplied by $Q_{10}^{(T_{s,i} - T_{ref})/10}$. In CLM, a default Q_{10} of 1.5 is used for both maintenance respiration and decomposition. However, nighttime CO_2 flux measurements above the canopy at Wind River, which would include the sum of autotrophic and heterotrophic respiration, indicate a Q_{10} of 2.49 (Misson et al., 2007). By adjusting CLM's Q_{10} to 2.5 for both maintenance respiration and decomposition, the seasonal behavior of ecosystem respiration better corresponded with observed values. This was especially the case for heterotrophic respiration, reducing the model overestimation during winter and the model underestimation during summer.

A7 Soil Hydraulic Properties

Initial runs indicated poor performance of CLM in the simulation of soil water content at the Wind River site (strong dry bias), which resulted in an unrealistic down-regulation of GPP due to soil moisture~~drought~~ stress late in the dry, summer season. When using the original soil hydraulic properties from CLM v.4.0 the results were greatly improved, with a wetter soil and a reduction of the unrealistic soil moisture stress~~drought effect~~. The observed improvement was likely related to a smaller subsurface runoff in CLM v.4.0 and consequently greater water retention in the soil. In CLM, subsurface runoff is proportional to a term representing the maximum drainage when the water table depth is at the surface (q_{drai}^{max}). In CLM v.4.0, $q_{drai}^{max} = 0.0055$ kg m^{-2} s^{-1}, while in CLM v.4.5 $q_{drai}^{max} = 10 \sin\beta$ kg m^{-2} s^{-1}, where β is the mean grid cell topographic slope. Even for a small 1^{o} slope, q_{drai}^{max} is significantly larger than in CLM v.4.0 (0.1745 kg m^{-2} s^{-1}). The soil hydraulic properties from CLM v.4.0 were therefore used in this study.

A8 Root Distribution

In CLM, root distribution over soil depth is calculated as in Eq. (4). ~~(Oleson et al., 2013):~~

~~$$r_i = 0.5(e^{-r_a z_{h,i-1}} + e^{-r_b z_{h,i-1}}) - 0.5\alpha(e^{-r_a z_{h,i}} + e^{-r_b z_{h,i}}) \quad (A3)$$~~

~~where r_i is the root fraction at the soil layer i, $z_{h,i}$ (m) is the depth from the soil surface to the interface between layers i and $i+1$ ($z_{h,0} = 0$ corresponds to the soil surface), r_a and r_b are root distribution parameters (m^{-1}), $\alpha = 1$ for $1 \leq i < N_{levsoi}$, and $\alpha = 0$ for $i = N_{levsoi}$ (N_{levsoi} is the number of soil layers). The sum of r_i over the whole soil column is equal to 1.~~ Root fraction (r_i) in combination with a plant wilting factor (w_i~~,~~ ~~(function of soil water potential and a plant-dependent response to drought stress~~Eq. 5) for each soil layer i are used to calculate an integrated ~~drought~~ soil moisture stress parameter in CLM, β_t (Eq. 3), which downregulates stomatal conductance in the model (~~see Sect. 2.1;~~ Eq~~s~~. 2 ~~and 3~~).

Shaw et al. (2004) provides a good description of rooting depth at Wind River: "Plant roots are concentrated above 50 cm in soil profiles; however, roots as deep as 2.05 m have been observed in younger forests growing on nearly identical soils (T. Hinckley personal communication). Many coarse roots of Douglas-fir extend to depths greater than 1.0 m. Tip-up mounds of windthrown western hemlock trees typically have a classic flat root plate indicative of shallow rooting" (Douglas-fir and western hemlock are the dominant species at the site). With the default NETT PFT root distribution parameters in Eq. (4) ($r_a = 7$ m^{-1} and $r_b = 2$ m^{-1}), the total root fraction in the top 46 and 130 cm of soil is 78% and 96%, respectively (note the small fraction of roots at depths below 1.3 m (4%)). The above site description (Shaw et al. 2004) suggests that the default parameters are inadequate at Wind River, resulting in a "too-shallow" rooting profile.

Comment [HFD32]: [RC1.13]

~~The default root distribution parameters for the NETT PFT are $r_a = 7$ m^{-1} and $r_b = 2$ m^{-1}.~~ In this study the NETT PFT r_b parameter ~~for the NETT PFT~~ was changed to 1 m^{-1} (default CLM value for broadleaf evergreen temperate tree PFT~~plant functional type~~), shifting roots towards deeper soil layers, in order to make water stored at deeper soil layers available to the trees and, along with the changes in the soil hydraulic properties discussed in Appendix~~Sect.~~ A7, reduce the excessive late-summer soil moisture stress and downregulation of GPP in the model~~minimize the model overestimation of drought stress at the Wind River site during late summer.~~ ~~.~~With the adjusted r_b parameter, the total root fraction in the top 46 and 130 cm of soil is 67% and 86%, respectively (14% below 1.3 m), which seems more reasonable based on Shaw et al. (2004) and the fact that Douglas-fir trees at the site are about 500 years old and 40–65-m tall. The adjustment of soil moisture stress in CLM via root distribution was therefore physically justified.

The plant wilting factor, w_i, offers an additional path for adjustment of the simulated soil moisture stress, but it was not investigated in this study.

Comment [HFD33]: [RC2.3]

A9 Stomatal Conductance

In CLM, leaf stomatal conductance is calculated based on the Ball-Berry model as described by Collatz et al. (1991) and implemented by Sellers et al. (1996) in the SiB2 model (see Eq. 2). The default values set for the parameters m_{bb} and b_{bb} in CLM for C$_3$ plants (9 and 10 mmol m^{-2} leaf s^{-1}, respectively) were found to be inadequate at Wind River, leading to a significant overestimation of latent heat fluxes due to excessive plant transpiration (after the adjustments discussed in the

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aforementioned Sections which resulted in higher forest productivity). These default parameter values were established based on the values used in the SiB2 model (Sellers et al., 1996). In SiB2, however, a distinction was made for coniferous forests ($m_{bb} = 6$) but was not carried over to CLM. Observations reported in the literature support this lower m_{bb} value for conifers (see for example the survey by Williams et al., 2004, Table 6.3, and Miner et al., 2017, Fig. 1). On the other hand, b_{bb} values reported in the literature are highly variable (1–400 mmol m^{-2} leaf s^{-1} in the survey by Barnard and Bauerle, 2013 for a broad range of plant species). In CLM v.4.0, the default b_{bb} for C_3 plants is significantly smaller than in CLM v.4.5 (2 vs. 10 mmol m^{-2} leaf s^{-1}) (Oleson et al., 2010). $m_{bb} = 6$ and $b_{bb} = 5$ mmol m^{-2} leaf s^{-1} were found to greatly improve the modeled latent heat fluxes at the Wind River site, and were therefore adopted in this study. The updated values also resulted in a great improvement in the simulation of δ^{13}C of leaves, SOM, and GPP. Figures A1 and A2 illustrate the impact of the stomatal conductance parameters on model performance, particularly in regards to latent heat fluxes and photosynthetic ^{13}C discrimination.

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It is important to highlight that the default nitrogen limitation scheme was used in the simulations. As discussed in Sect. 2.1, this scheme makes CLM a partially-coupled model in respect to net leaf photosynthesis and stomatal conductance: while the actual GPP is down-regulated in response to nitrogen availability, stomatal conductance remains consistent with potential net leaf photosynthesis (A_n). With this structure, CLM is expected to overestimate plant transpiration and photosynthetic ^{13}C discrimination. The above discussed calibration of the Ball-Berry stomatal conductance parameters, especially the significant reduction of m_{bb} from 9 to 6, must also have compensated for this structural issue within the model.

Comment [HFD34]: [RC2.1.2]

When using the default nitrogen limitation scheme in CLM, the modeled ^{13}C discrimination values reported by Raczka et al. (2016) for the Niwot Ridge AmeriFlux site (also a coniferous forest site) were significantly overestimated, i.e., δ^{13}C values of GPP and biomass were significantly smaller than observations. To improve the simulation, Raczka et al. (2016) removed the post-photosynthetic nitrogen down-regulation of A_n and GPP_{pot} ($d = 0$; see Eq. 9) and included a foliar nitrogen-limiting factor in the calculation of V_{cmax25}, making the model fully coupled in respect to net leaf photosynthesis and stomatal conductance. With this configuration, their simulation of ^{13}C discrimination improved significantly, but the values still presented a small overestimation in respect to the site observations. According to Raczka et al. (2016), overestimation of g_s due to an inadequate m_{bb} value (too high) could be a reason for the mismatch (they used the default value of 9 in their simulation).

The alternative nitrogen limitation scheme (via V_{cmax25} down-regulation, as in Raczka et al., 2016) was also investigated here. The simulation of LE, GPP, and ^{13}C discrimination when using this configuration and the default m_{bb} value of 9 was found to be similar to the results when using the default nitrogen limitation scheme and $m_{bb} = 6$ (Fig. A3). The results in Fig. A3 indicate that the calibration of m_{bb} from 9 to 6 represents a tradeoff with the approach to nutrient limitation, compensating for elevated, nitrogen-unlimited (potential) net leaf photosynthesis used in the calculation of g_s.

A10 CLM Performance: Default vs. Calibrated Parameters

Comment [HFD35]: [RC1.11]

In order to illustrate the effect of altering the model parameters discussed in this Appendix (see summary of changes in Table 1), Figs. A4 and A5 compare the performance of CLM for key model outputs when using "out-of-the-box" parameters and calibrated parameters. Note the significant improvement in the simulation of LAI, biomass, and CO_2/H_2O fluxes.

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Table 1. Summary of changes in CLM parameters during the calibration process. The parameters listed, excluding M, Q_{10}, m_{bb}, b_{bb}, and soil hydraulic parameters, correspond to the needleleaf evergreen temperate tree plant functional type (NETT PFT).

Parameter	Description	CLM name	Default CLM value	Calibrated CLM value
$A_{s:l}$	New stem C: new leaf C ratio (gC gC^{-1})	*stem_leaf*	Dynamic	2
$A_{fr:l}$	New fine root C: new leaf C ratio (gC gC^{-1})	*froot_leaf*	1	0.385
CN_l	Leaf C:N ratio (gC gN^{-1})	*leafcn*	35	38.2
CN_{llit}	Leaf litter C:N ratio (gC gN^{-1})	*lflitcn*	70	76.4
CN_{fr}	Fine root C:N ratio (gC gN^{-1})	*frootcn*	42	64.7
τ_l	Leaf longevity (yr)	*leaf_long*	3	5
r_b	Root distribution parameter (m^{-1})	*rootb_par*	2	1
SLA_0	Specific leaf area at canopy top (m^2 leaf gC^{-1})	*slatop*	0.010	0.006
m	SLA(x) slope (m^2 ground gC^{-1})	*dsladlai*	0.00125	0.000985
M	Plant mortality rate (% yr^{-1})	*am*	2	1.5
Q_{10}	Temperature sensitivity coefficient of maintenance respiration and decomposition (–)	*q10*	1.5	2.5
Soil hydraulic parameters	Version used	*origflag* (namelist variable)	0 (CLM4.5)	1 (CLM4.0)
m_{bb}	Ball-Berry Eq. slope (–)	*mbbopt*	9	6
b_{bb}	Ball-Berry Eq. intercept (μmol m^{-2} leaf s^{-1})	*bbbopt*	10000	5000

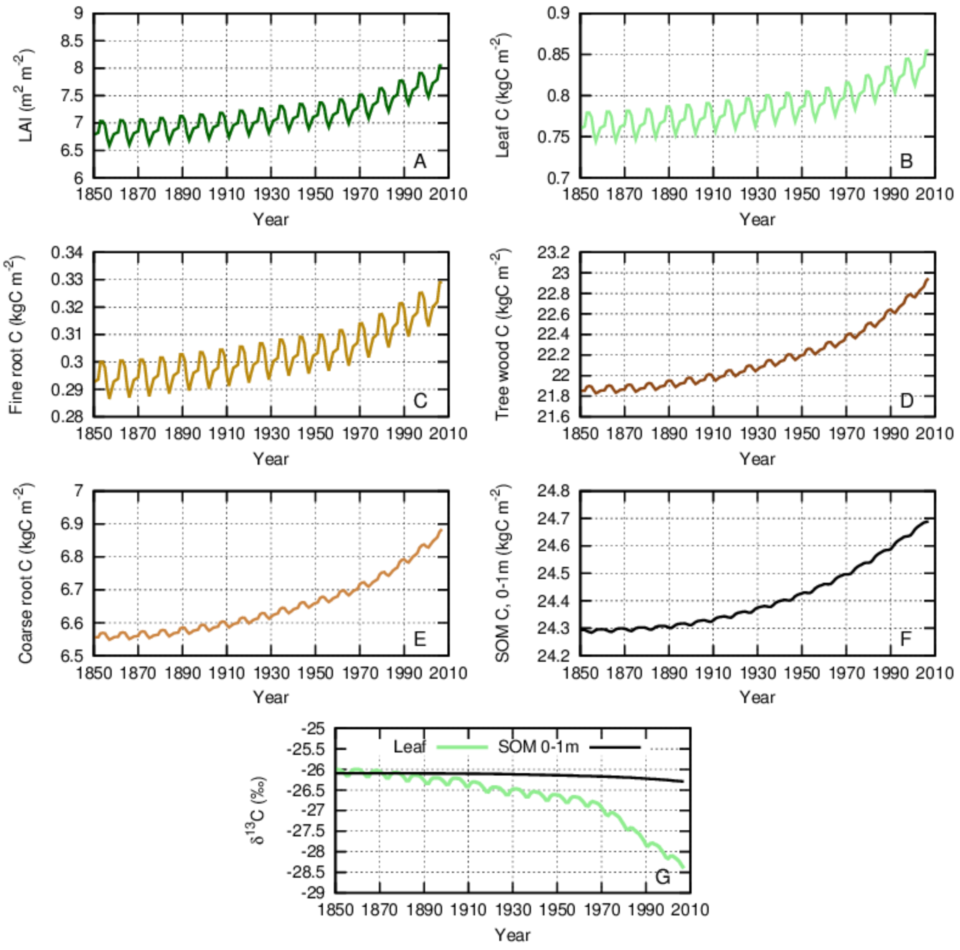
~~**Table 2.** Modeled leaf area index, biomass, and δ^{13}C values vs. observations. CLM results reported here are annual averages at the end of the transient run (year 2006). CLM δ^{13}C values were calculated from annual averages of the respective ^{13}C and ^{12}C pools.~~

Comment [HFD36]: [RC1.9]

~~Variable~~	~~CLM~~	~~Observation~~	~~Reference~~
~~LAI (m^2 leaf m^{-2} ground)~~	~~8.0~~	~~9.3 ± 2.1~~	~~AmeriFlux database~~
~~Leaf carbon (gC m^{-2} ground)~~	~~855~~	~~941 ± 322~~	~~AmeriFlux database~~
~~Fine root carbon (gC m^{-2} ground)~~	~~329~~	~~362 ± 26~~	~~AmeriFlux database~~
~~Tree wood carbon (gC m^{-2} ground)~~	~~22946~~	~~21918 ± 1349~~	~~AmeriFlux database~~
~~Coarse root carbon (gC m^{-2} ground)~~	~~6884~~	~~8122 ± 639~~	~~AmeriFlux database~~
~~SOM carbon, 0–1 m (gC m^{-2} ground)~~	~~24689~~		
~~δ^{13}C leaf (‰)~~	~~−28.401~~	~~−28.2 to −26.3 (TC[a])~~	~~Fessenden and Ehleringer (2003), Fig. 2b~~
		~~−29.5 to −28.2 (MC[a])~~	
		~~−34.2 to −32.4 (BC[a])~~	
~~δ^{13}C SOM, 0–1 m (‰)~~	~~−26.294~~	~~−26.5 to −25.0 (20 cm)~~	~~Fessenden and Ehleringer (2003), Fig. 3~~

~~[a] TC, MC, and BC stands for top, middle, and bottom canopy, respectively~~

Figure 1. Location and view of the Wind River AmeriFlux site, US-Wrc (satellite image from Google Earth).


LAI (m^2 m^{-2})
9
8.5
8
7.5
7
6.5
6
A
Leaf C (kgC m^{-2})
0.9
0.85
0.8
0.75
0.7
B
Fine root C (kgC m^{-2})
0.34
0.33
0.32
0.31
0.3
0.29
0.28
C
Tree wood C (kgC m^{-2})
23.2
23
22.8
22.6
22.4
22.2
22
21.8
21.6
D
Coarse root C (kgC m^{-2})
7
6.9
6.8
6.7
6.6
6.5
E
SOM C, 0-1m (kgC m^{-2})
24.8
24.7
24.6
24.5
24.4
24.3
24.2
F
δ^{13}C (‰)
-25
-25.5
-26
-26.5
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-28
-28.5
-29
Leaf
SOM 0-1m
G
1850 1870 1890 1910 1930 1950 1970 1990 2010
Year

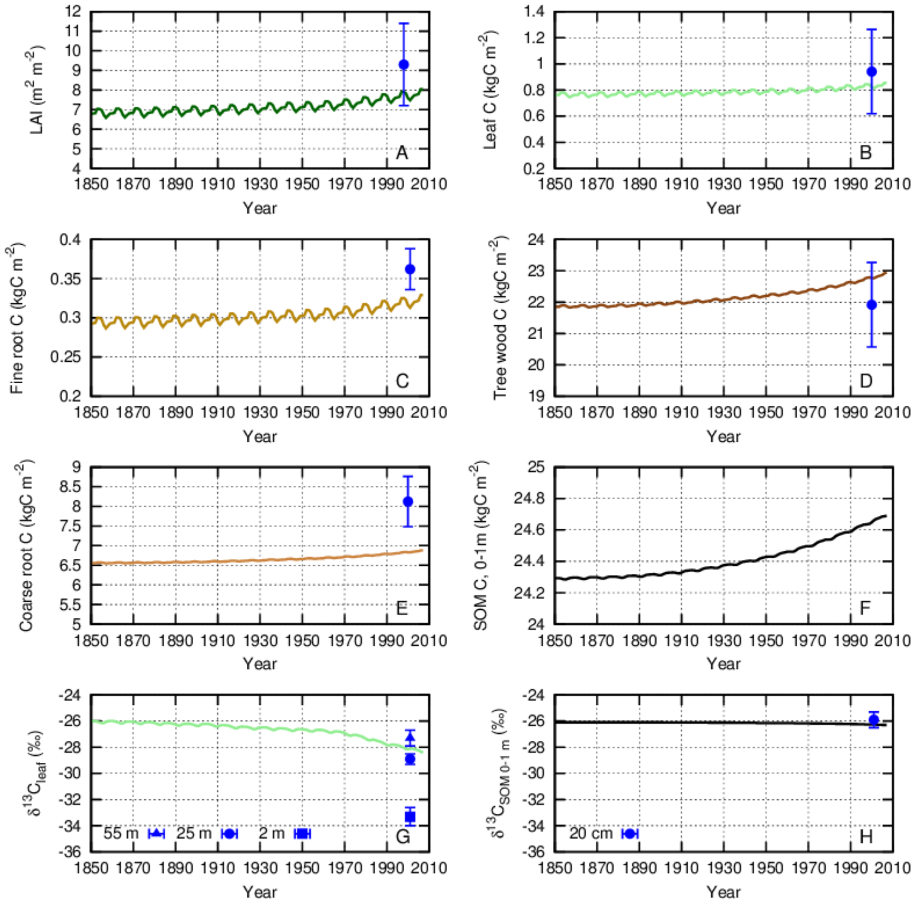

Figure 2. Modeled leaf area index (A), carbon stocks (B–F), and $\delta^{13}C$ of leaf (G) and soil organic matter (~~G~~H) during the transient run (lines) compared against site observations (points and error bars). Modeled v~~V~~alues in panels A–F correspond to annual averages. Modeled~~The~~ $\delta^{13}C$ values in panels G and H were calculated from annual averages of the respective ^{13}C and ^{12}C pools. Observations in panels A–E (average ± std. dev.) are from the AmeriFlux database (based on Thomas and Winner, 2000 and Harmon et al., 2004). Observations in panels G and H correspond to the average ± std. dev. of the measurements reported by Fessenden and Ehleringer (2003) in their Figs. 2b and 3 (leaf $\delta^{13}C$ at canopy top (55 m), middle (25 m), and bottom (2 m) and SOM $\delta^{13}C$ at 20 cm depth).

Comment [HFD37]: [RC1.9]

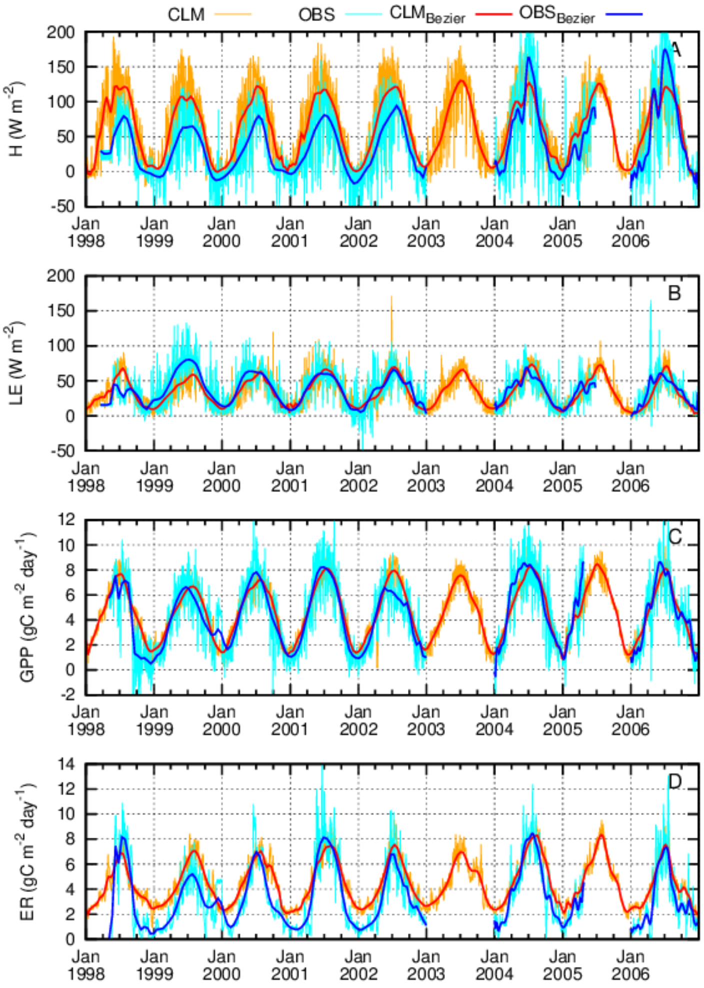

Figure 3. Modeled sensible heat flux (A), latent heat flux (B), gross primary production (C), and ecosystem respiration (D) vs. site observations. Orange/red and cyan/blue lines correspond to modeled and observed values, respectively. For a clearer visualization, the daily averages (thin lines) were smoothed with a Bézier algorithm (thick lines).

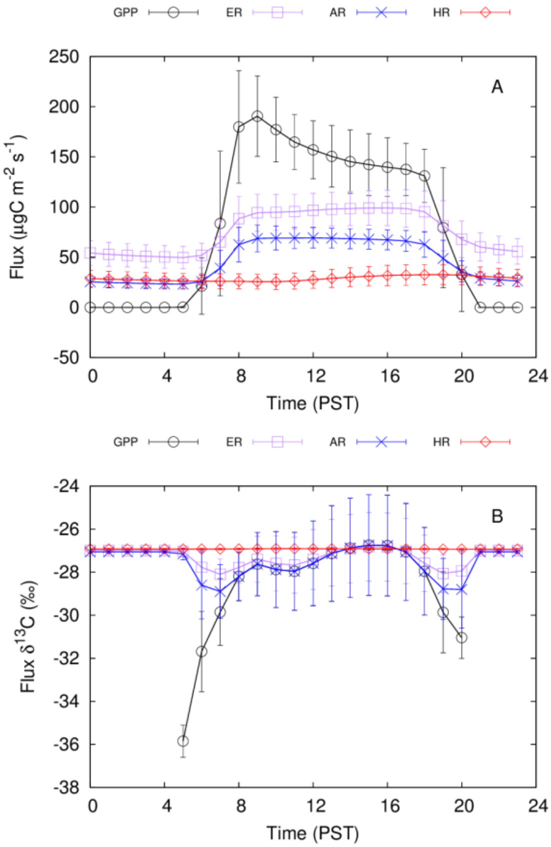

Figure 4. Mean diurnal cycle of modeled carbon fluxes (A) and their respective carbon isotope ratios (B) for the summer months (June–September) of years 1998–2006. Fluxes include gross primary production (black circles), ecosystem respiration (purple squares), autotrophic respiration (blue crosses), and heterotrophic respiration (red diamonds). Bars correspond to ±1 standard deviation.

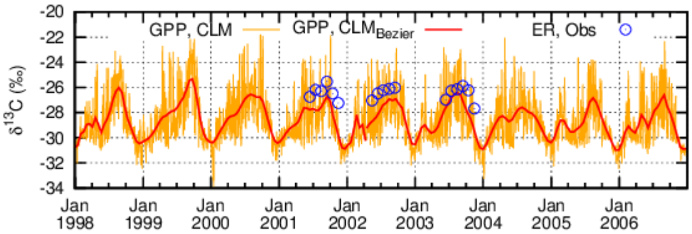

Figure 5. Modeled δ^{13}C of gross primary production (lines) and observed δ^{13}C of ecosystem respiration (circles). Thin orange line corresponds to daily averages using 10:00–16:00 data only. For a clearer visualization, this curve was smoothed with a Bézier algorithm (thick red line). Blue circles correspond to site observations (monthly averages) reported by Lai et al. (2005).

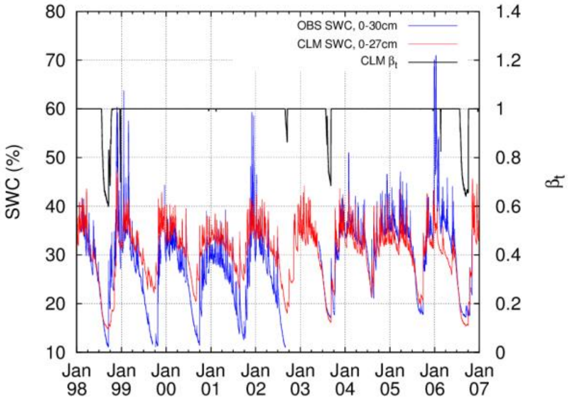

Figure 6. Hourly soil water content and CLM's soil moisture~~drought~~ stress parameter, β_t (black line). Observed SWC (blue line) corresponds to the integrated value for the top 30 cm of soil, while modeled SWC (red line) corresponds to the integrated value for the top 5 soil layers in CLM (0–27 cm). At Wind River, SWC at permanent wilting point and at field capacity is 14% and 30%, respectively (Wharton et al., 2009).

Comment [HFD38]: [RC2.9]

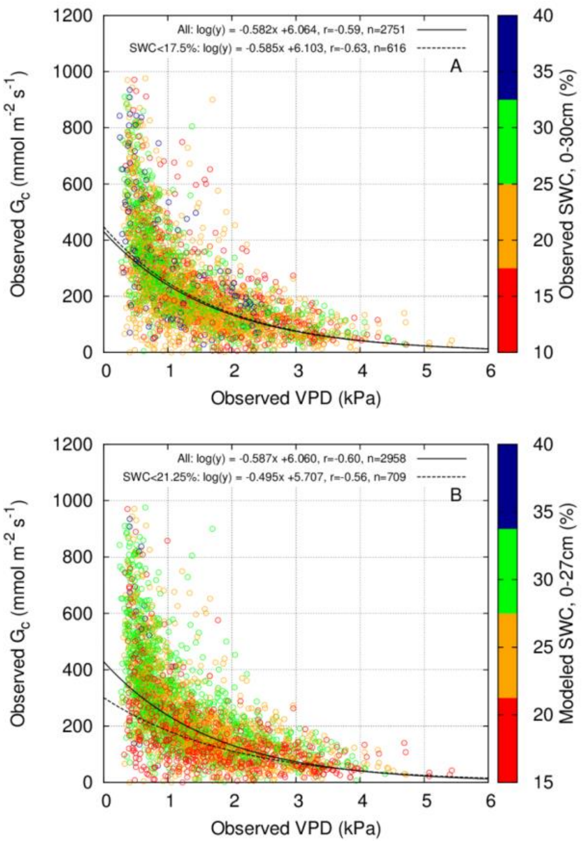

Figure 7. Hourly observed canopy conductance vs. observed VPD for the summer months (June–September) of years 1999–2006, restricted to 10:00–16:00 PST (additional restrictions were imposed to the calculation of G_c, see Sect. 2.7). Years 1998 and 2005 were not included due to missing data. Data points were segregated according to observed SWC in panel A and according to modeled SWC in panel B (see Fig. 6). Lines correspond to the linear regression between $\log G_c$ and VPD using all data points (solid lines) and using only points within the lowest SWC bin (red circles, dashed lines).

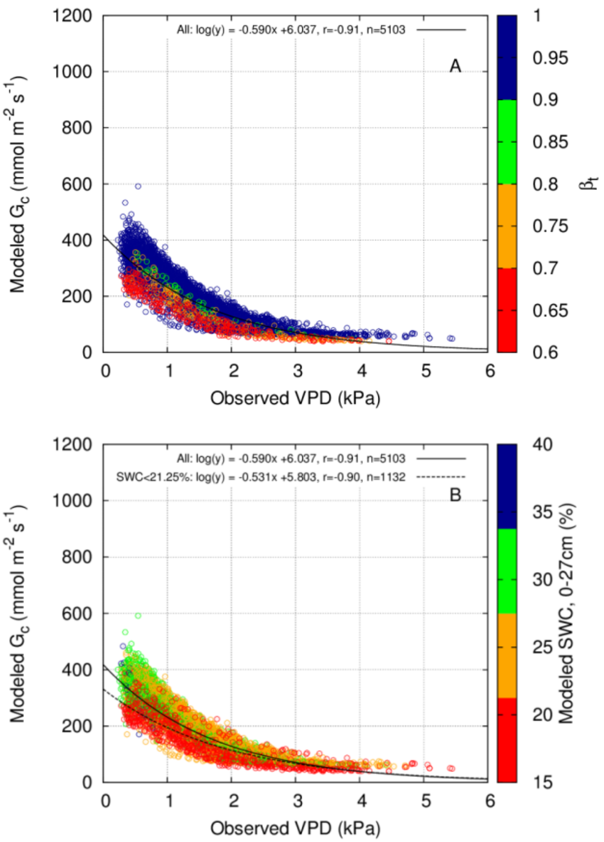

Figure 8. Hourly modeled canopy conductance vs. observed VPD for the summer months (June–September) of years 1999–2006, restricted to 10:00–16:00 PST (additional restrictions were imposed to the calculation of G_c, see Sect. 2.7). Note that observed air temperature and relative humidity were used to drive CLM. Years 1998 and 2005 were not included for consistency with Fig. 7. Data points were segregated according to the soil moisture~~drought~~ stress parameter β_t in panel A and according to modeled SWC in panel B (see Fig. 6). Lines correspond to the linear regression between $\log G_c$ and VPD using all data points (solid lines) and using only points within the lowest SWC bin (red circles, dashed line).

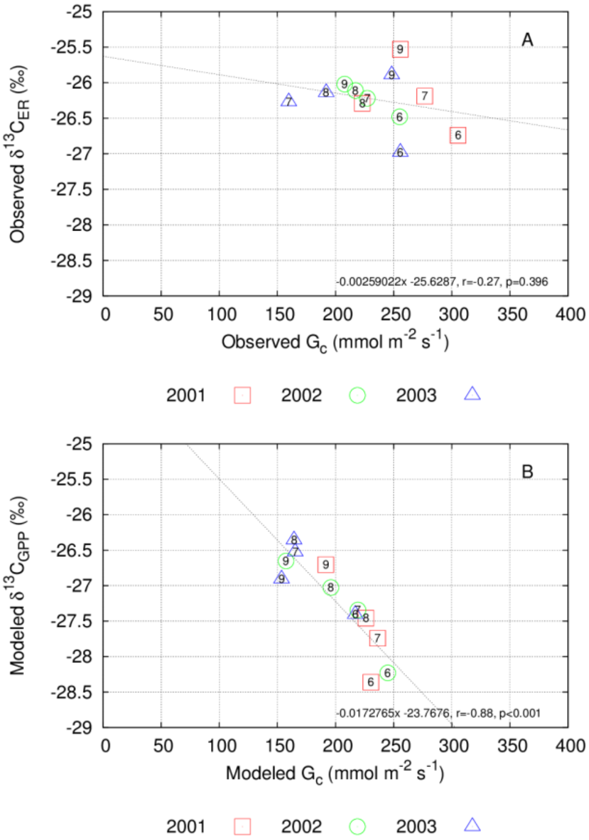

Figure 9. Observed δ^{13}C of ecosystem respiration vs. observed canopy conductance (A) and modeled δ^{13}C of gross primary production vs. modeled canopy conductance (B) for the summer months of 2001–2003. Except for the observed $\delta^{13}\mathrm{C}_{\mathrm{ER}}$, data points correspond to monthly averages of daytime (10:00–16:00) data (additional restrictions were imposed to the calculation of G_c, see Sect. 2.7). Observed $\delta^{13}\mathrm{C}_{\mathrm{ER}}$ corresponds to the monthly averages reported by Lai et al. (2005). Numbers at the center of each point indicate the month.

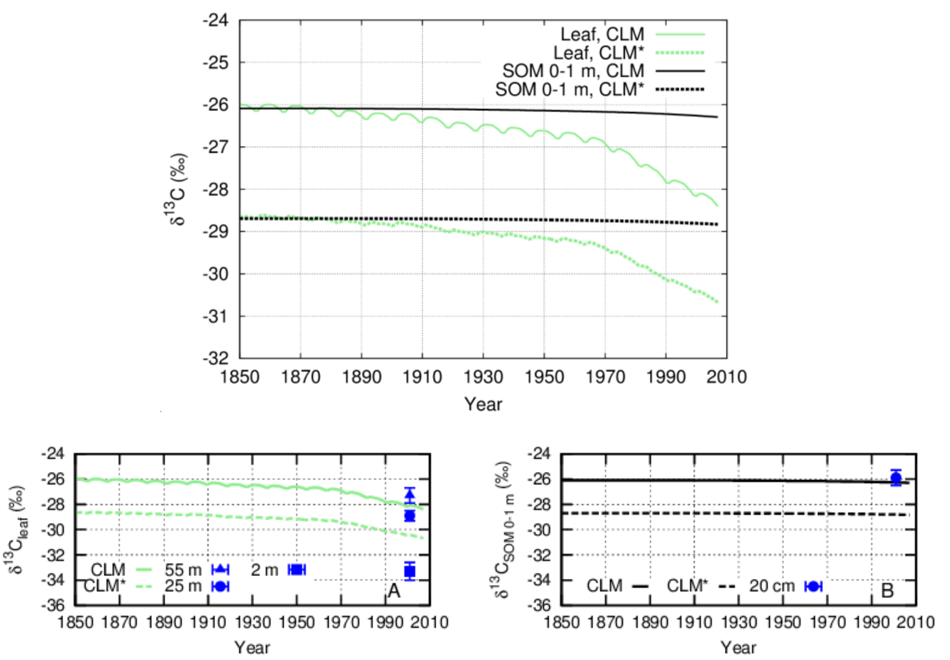

Figure A1. Modeled δ^{13}C of leaf (A) and soil organic matter (B), ~~(~~calculated from annual averages of the respective ^{13}C and ^{12}C pools~~)~~ during the transient run (lines) ~~(green and black lines, respectively)~~. Results from two model configurations are presented: CLM (calibrated model, solid lines) and CLM* (calibrated model using the default stomatal conductance parameters (m_{bb} and b_{bb}; see Table 1), dashed lines). Site observations (average ± std. dev., blue points and error bars) are also shown (see caption of Fig. 2 for details).~~cf. Table 2.~~

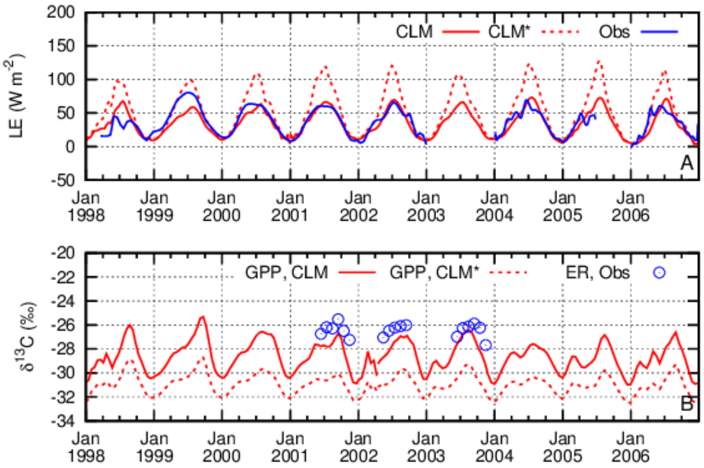

Figure A2. Modeled latent heat flux (A) and δ^{13}C of gross primary production (B, lines) for 1998–2006. The curves presented correspond to Bézier-smoothed daily averages as in Figs. 3 and 5. Results from two model runs are presented: CLM (calibrated model, solid red lines), and CLM* (calibrated model using the default stomatal conductance parameters 5 (m_{bb} and b_{bb}; see Table 1), dashed red lines). The blue line and circles correspond to site observations. The circles in panel B are the monthly averages of δ^{13}C$_{ER}$ reported by Lai et al. (2005).

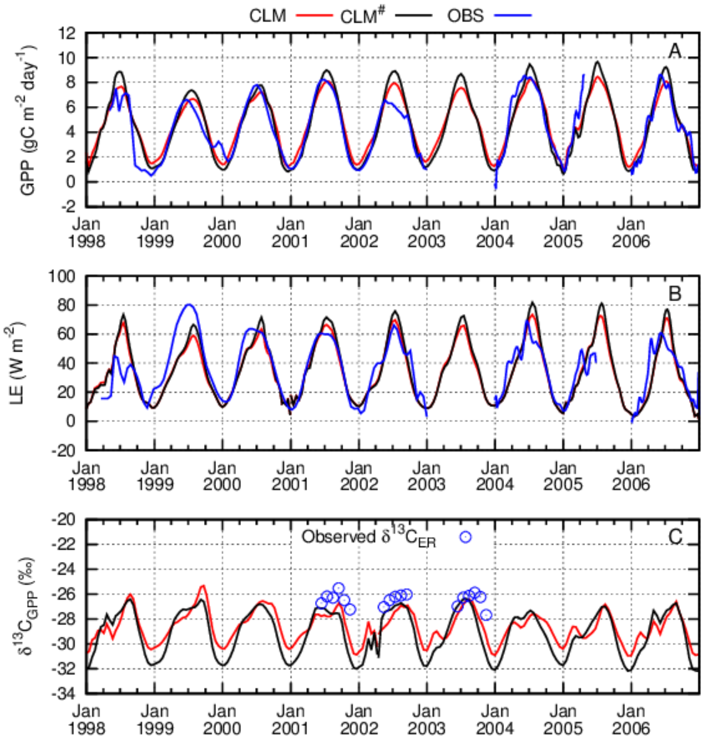

Figure A3. Modeled gross primary production (A), latent heat flux (B), and δ^{13}C of gross primary production (C) for 1998–2006. The curves presented correspond to Bézier-smoothed daily averages as in Figs. 3 and 5. Results from two model runs are presented: CLM (calibrated model, red lines), and CLM$^{\#}$ (calibrated model using $m_{bb} = 9$ and the alternative nitrogen limitation scheme discussed in Appendix A9, black lines). In CLM$^{\#}$, V_{cmax25} was multiplied by a seasonally-varying nitrogen down-regulation factor, $f_n(x) = -1.39697\times10^{-14}x^6 + 1.71948\times10^{-11}x^5 - 8.26883\times10^{-9}x^4 + 1.90682\times10^{-6}x^3 - 1.97639\times10^{-4}x^2 + 0.0055728x + 0.966272 - 0.35 \leq 1$ (x = day of year), calculated based on the mean (1850–2006) seasonal cycle of $\mathrm{GPP}/\mathrm{GPP}_{\mathrm{pot}} = 1 - d$ in the CLM run subtracted by 0.35 (manual adjustment applied to avoid excessive productivity during the transient simulation). Blue lines and circles correspond to site observations. The circles in panel C are the monthly averages of $\delta^{13}\mathrm{C}_{\mathrm{ER}}$ reported by Lai et al. (2005).

Comment [HFD39]: [RC2.1.2]

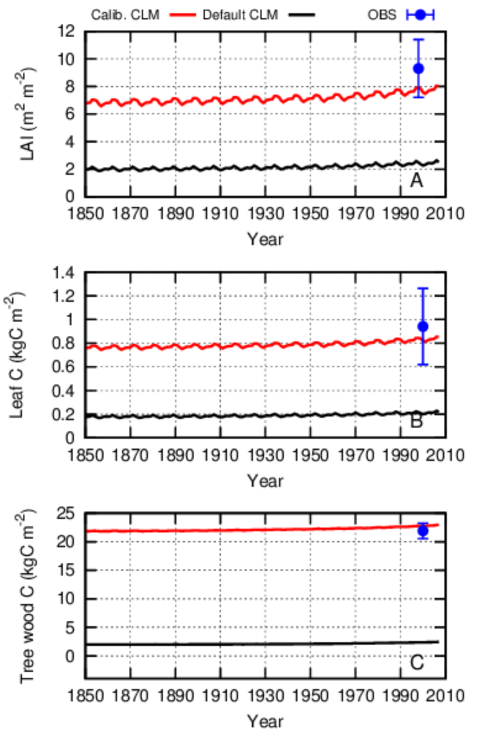

Figure A4. Comparison of CLM performance at Wind River when using default, "out-of-the-box" parameters (black lines) and calibrated parameters (red lines). Modeled values correspond to annual averages. Observations (average ± std. dev., blue points and error bars) are from the AmeriFlux database (based on Thomas and Winner, 2000 and Harmon et al., 2004).

Comment [HFD40]: [RC1.11]

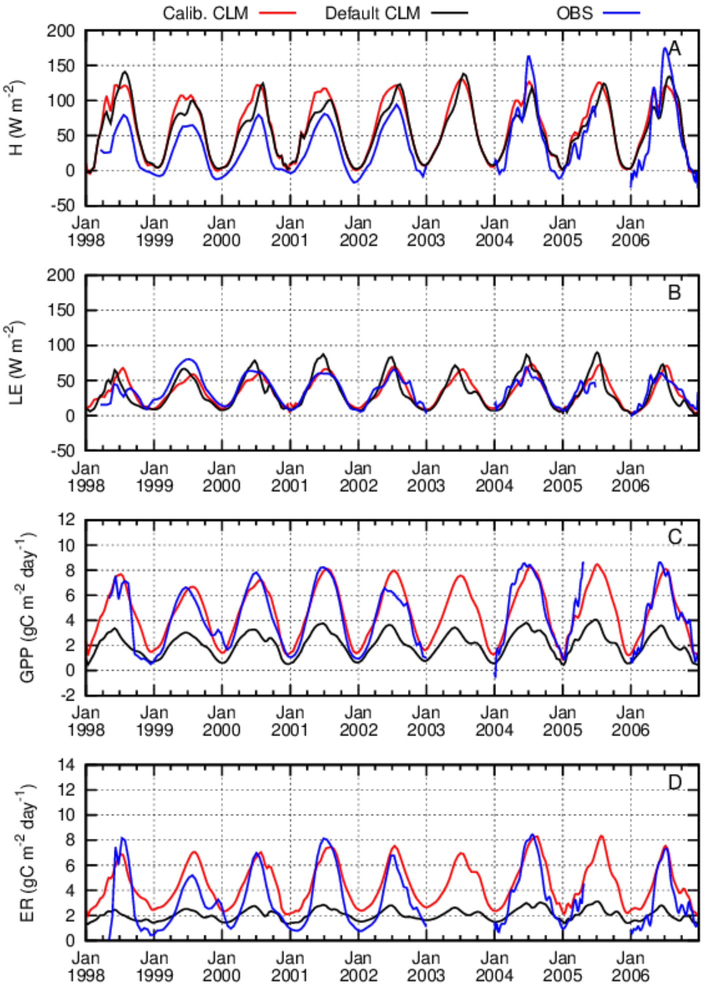

Figure A5. Comparison of CLM performance at Wind River when using default, "out-of-the-box" parameters (black lines) and calibrated parameters (red lines). Observations (blue lines) are from the AmeriFlux database. For a clearer visualization, the data presented correspond to Bézier-smoothed daily averages as in Fig. 3.

Comment [HFD41]: [RC1.11]