

Interactive comment on “The Polar Vegetation Photosynthesis and Respiration Model (PolarVPRM): a parsimonious, satellite data-driven model of high-latitude CO₂ exchange” by K. A. Luus and J. C. Lin

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Dear Editors and Referees,

Thank you for providing an excellent review of this article, and for providing insightful comments. The manuscript has been greatly improved by completing all revisions suggested, as detailed in the responses below. All comments and remarks from Referees are provided (a), followed by author responses (b), and changes made to the manuscript (c).

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1 Response to Anonymous Referee #1

1.1 General comments

1. a) *The manuscript by K. Luus and J. Lin describes PolarVPRM, A model that computes high-latitude NEE with descriptions of photosynthesis and respiration that are regulated by remotely sensed driving variables. The manuscript describes specifically the additions to VPRM that were made for high-latitude applications. PolarVPRM applies seven vegetation classes, of which four were simulated using the equations and parameterization as in the original VPRM. The remaining three classes (barren/wetland, graminoid tundra and shrub tundra) were calibrated and validated against a number of eddy covariance sites in North America. Apart from this calibration and validation, the manuscript addresses the differences between PolarVPRM NEE estimates and estimates from two other model products, and it analyses the trends in NEE for the period 2001-2012. Overall, this is a thorough paper with a clear description of the model, its calibration and validation, and well-suited for publication in GMD. Some unclarities remain as to how the calibration has taken place, and I have some remarks on the results and discussion, but I am confident that the authors can address these in a revised version. Please find my remarks below (with reference to page/line numbers).*
b) Thank you for the positive and thorough review.

1.2 Major remarks

1. a) 985/26: *It is unclear how LSWImax (Eq. 3), Tmin, Tmax and Topt (Eq. 4) were determined, if not from the calibration procedure. The temperature parameters are mentioned later (989/5) as originating "from the calibration sites", but it is unclear whether these parameters are specific to the vegetation class or generic, and how these were determined.*

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b) LSWImax was calculated as the maximum MODIS LSWI for each pixel per year, and was not further modified. Tmin, Topt and Tmax are the same as in Mahadevan (2008), and the values are not optimized for each vegetation class for the same reasons as described by Mahadevan. Mahadevan's values were used for non-arctic vegetation classes, and for all vegetation types, Tmin=0C and Tmax=40C. Topt was set using approximations of values found in literature. This now appears in the initial presentation of GEE equations rather than in model calibration, as no tuning took place for LSWImax, Tmax, Topt or Tmin.

c) "LSWI_{max} refers to the maximum annual pixel-specific LSWI value. For barren/wetland regions (which include the Canadian High Arctic), a T_{opt}=10° C, whereas T_{opt}=15° C over shrub tundra and graminoid tundra, as according to e.g. Tieszen (1973); Chapin III (1983). Plots of air temperature and growing season NEE at calibration sites were then checked to ensure these values appeared reasonable, but no optimization took place, to avoid correlation and parameter instability (Mahadevan et al., 2008)."

2. a) 994/4 (Validation): *The validation section describes that MBE and RMSE were determined at 3-hourly, daily and monthly intervals, but this section reports only the 3-hourly values. It would be interesting to see how well the estimates were at daily or monthly scale: 3-hourly values provide primarily insight in the model's ability to capture the di-urnal cycle, whereas the daily and monthly values would give more insight in the ability regarding seasonal variations. I would recommend the authors to address the sea-sonal variations as well. Likewise, it would be interesting to see how good the model captures the interannual variability, which is typically much harder to simulate. How- ever, I can imagine that the amount of validation data may not be enough to analyse this.*

b) Yes, good point. The daily error metrics are now reported in addition to three-hourly and monthly error metrics in Table 5.

I agree that the question of inter-annual variability is very interesting, and I also

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agree that these questions cannot be comprehensively answered using only the data and model outputs presented in this paper, which contain more gaps during the snow season than growing season, and more gaps in some years than others. Due to differences in data availability, some comparisons against model estimates yield lower error metrics than other years, not necessarily because either the model predicted it incorrectly to be an anomalous year, or because the model could not capture an anomaly. Gap filling of data would permit insights to be gained into the net C exchange between years, but this would then involve comparisons between two models essentially. Thoroughly untangling the reasons why model performance varies over time, and why some anomalies in NEE are captured while others are not, are beyond the scope of the present manuscript, which aims to provide an initial description, validation, and trend analysis of PolarVPRM outputs. For statistics on model performance at Ivotuk (2004–7) and Daring Lake (2004–7), please refer to Luus et al. (2013a).

c) Please refer to Table 5, which has been expanded as requested to include daily error statistics. The methodology and discussion of results now also mention the daily results.

3. a) 1001/11: *The authors stress in their conclusions the changes from VPRM to PolarVPRM, but, whereas a comparison has been made to two other models, there is no comparison to the original VPRM in the manuscript. Therefore, the statement that "ac- curacy of snow season estimates has improved" is not supported by the manuscript. It would be nice, though, to have a short summary of how PolarVPRM compares to VPRM earlier in the manuscript. Such a summary could emphasize the importance of capturing these specific high-latitude dynamics, and would as such strengthen the study.*

b) I agree, the work presented here does not delve into differences between the VPRM and PolarVPRM frameworks, and the conclusions and model description have been modified accordingly (in c). Previous work outlined the feasibility of

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including snow observations into models of NEE (Luus et al., 2013c), and allowed insights to be gained into how VPRM's structure could best be modified in order to improve snow season estimates of NEE (Luus et al., 2013a). From the conclusions of Luus et al. (2013a): "The feasibility of incorporating remote sensing observations of snow into models of NEE was demonstrated by findings showing: (1) good agreement between time-lapse camera (<10 m) and remote sensing estimates of snow cover area (SCA) from Landsat (30 m) and MODIS (500 m); and (2) associations between in situ NEE and SCA at Daring Lake, NWT (May–June 2010). Uncertainty in VPRM estimates of NEE at two low Arctic sites was reduced by representing the decoupling effects of a snowpack on Tsoil and Tair. Estimating subnivean respiration as a function of Tsoil prevented respiration from being overestimated when it was limited by cool Tsoil at the start/end of the snow season, and enabled variability in cold season NEE to be simulated. The timing and magnitude of photosynthesis at the start and end of the snow season were best captured by GEE0, which used an implicit approach to simulate the influences of cold temperature, senescent vegetation and diminished sunlight on hindering photosynthesis. The resulting VPRM formulation, containing an implicit representation of the effects of SCA on photosynthesis and an explicit representation of the influence of SCA on respiration, had diminished RMSEs and MAEs across both sites and all years."

c) Introduction section 1.1: "Relative to VPRM, PolarVPRM uses different inputs (described in Appendix A), vegetation classes (presented in Luus et al. (2013b)), and model structure (selected in Luus et al. (2013a)), all of which improve its suitability for modeling high-latitude NEE. VPRM has previously been applied and validated across the USA and southern Canada (30–56N) (Mahadevan et al., 2008; Lin et al., 2011), and PolarVPRM can now be applied to generate estimates of NEE across high-latitude regions (e.g. north of 55N)."

Conclusions: "Furthermore, snow and growing season respiration are separately calculated according to air or soil temperature, which has previously been shown

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to improve accuracy in snow season estimates of NEE, relative to the standard VPRM framework (Luus et al., 2013a)."

1.3 Minor remarks

1. a) 980/21: *"enough to double or triple the atmospheric CO2 concentrations" - This is of course only valid if the compensating roles of marine and terrestrial uptake are not considered. As it is used in an illustrative manner here, it may not be so important, but one could phrase this more carefully as "ca. twice as much as the current atmospheric amount of C" (or likewise).*

c) Changed to: "more than twice the amount of carbon presently in the atmosphere."

2. a) 984/20: *Eq. 6: The mathematical notation with the condition in between the "R=" and the "alpha*..." is somewhat confusing, please alter to a more common notation with the condition at the end of the line.*

c) Please refer to the attached figure-1.png, which contains a screenshot of the equation found in the revised manuscript.

3. a) *Table 1, caption: A short sentence on the nomenclature used for the trees in the table would be helpful, to explain what "trees mixed mixed" means.*

c) Table 1 caption now includes: "SYNMAP tree classes are described according to leaf type (broad, needle or mixed) followed by leaf longevity (evergreen, deciduous, or mixed)."

4. a) 985/26: *A reference to Eqs. 5 and 6 would be helpful here.*

c) "Two parameters are used to calculate GEE [Eq. 5], and four parameters are used to calculate respiration [Eq. 6]"

5. a) *It would be good to mention here that these numbers refer to 3-hourly values.*

b) I wasn't sure exactly which section you meant I should include this in, so I

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added it in three times where it was relevant and had not previously been included.

c) "Briefly, PolarVPRM estimates of three-hourly NEE were validated [...] All parameters except λ were set according to half-hourly EC and meteorological observations, and λ was set using observations averaged to three-hourly timescales to match the temporal resolution of PolarVPRM [...] PolarVPRM three-hourly estimates of NEE showed excellent agreement with three-hourly averaged NEE."

6. a) 998/4 (Fig. 5): *It could be interesting to show Fig. 5b and 5c (multiplied by -1) in one panel, which would more easily show for which years R exceeds GEE (and reversed) - it would also illustrate that R varies more between years, whereas GEE is more stable.*

b) Thank you for this excellent suggestion. Combining respiration and $-1 \times \text{GEE}$ into a single plot provides a more intuitive representation of the contributions of respiration and photosynthesis to the net C balance of the NAHL region.

c) Figure 5 now shows R and $-1 \times \text{GEE}$ over time, plotted on the same axes, which is a very nice improvement over the previous display (please see figure-2.pdf attached).

7. a) 998/19: *Remove brackets around "Fig. 5b"*

c) "observed in Fig. 5b"

8. a) 999/11 (Fig. 7): *If possible, it would be nice to see the non-significant pixels in Fig. 7-9 coloured differently than the water body pixels.*

b) Water body pixels are shown in grey, and non-significant pixels are shown in white.

c) The caption for Fig. 7 now includes a note: "Pixels with $>50\%$ fractional water content are indicated in grey."

9. a) 1001/10: *The remark on day length variations comes rather late here (I have not noted it earlier in the manuscript) - if this is a difference between VPRM and*

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PolarVPRM, it should be brought up earlier.

b) Both VPRM and PolarVPRM are driven with shortwave radiation. Seasonal variations in the amount of incoming shortwave radiation are much larger over high-latitude regions than over the lower-latitude areas where VPRM had been applied. The benefits of using shortwave radiation as a main driver of GEE, rather than using more complex strategies that can dampen this signal, provides larger benefits over arctic regions than over low-latitude areas. This therefore isn't a change to the VPRM structure, but a potentially underrecognized benefit of the VPRM structure when applied to regions of the world which have less variability in day length.

c) "PolarVPRM adequately simulates high-latitude GEE because it captures spatial heterogeneity in polar NEE with Arctic-specific vegetation classes, and captures seasonal variations in day length which alter diurnal timing of photosynthesis, using shortwave radiation as a driver of GEE."

2 Response to Anonymous Referee #2

a) *"The Polar Vegetation Photosynthesis and Respiration Model (PolarVPRM): a parsimonious, satellite data-driven model of high-latitude CO₂ exchange", by Luus and Lin, presents revisions to the Vegetation Photosynthesis and Respiration Model (VPRM) of Mahadevan et al. (2008) seeking to better diagnose North American Arctic atmosphere-ecosystem carbon exchange. The authors address a timely and important topic (arctic carbon exchange) and the article is generally well-written.*

I have two significant first-order concerns about the study design that I feel should be addressed before the article is published. Those are described below, followed by more focused comments.

b) Thank you for providing a thorough and positive review of this article.

2.1 General comments

1. a) *My first high-level concern concerns the design of the model intercomparison portion of the study. The paper presents the PolarVPRM as an improvement over the VPRM in the high latitudes: "Model intercomparisons indicated that PolarVPRM showed slightly better agreement with eddy covariance observations relative to existing models" (P 980 L 11-12); "PolarVPRM contains a number of important differences in inputs and model structure relative to VPRM, and these allow PolarVPRM to generate accurate estimates of NEE across high-latitude regions." (P 982 L 2-4). Yet the study conspicuously avoids comparing PolarVPRM diagnoses to VPRM diagnoses. I expect the PolarVPRM to provide a better fit to eddy covariance net ecosystem exchange observations than the VPRM solely because it uses more parameters (six, vs. the VPRM's four). In my opinion a quantitative comparison to the VPRM using something like AIC (Aikake, 1976) is needed to justify the additional complexity contributed by those two parameters.*
 b) AIC scores were calculated for the portion of observations at Ivotuk which had $T_{soil} < 1^{\circ}C$ separately for each year (2004–2007):

Model	2004	2005	2006	2007
Tair	3163	3911	4780	1319
TAir & TSoil	3161	3910	4776	1211

For all years, AIC scores are lower when snow season respiration is calculated using soil temperatures and growing season respiration is calculated using air temperatures, than when respiration is calculated year-round from air temperatures.

The gap further widens when year-round respiration is calculated from a combination of soil and air temperatures. Although the addition of two new parameters increases complexity, this additional complexity diminishes errors in snow-season estimates of NEE.

- c) "Calculating subnivean respiration from soil temperature and growing season

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respiration from air temperature decreased model errors at two high-latitude sites (Daring Lake & Ivotuk), relative to other model formulations, including the original VPRM (Luus et al., 2013a). Furthermore, tests with data from Ivotuk (2004–7) using Akaike's Information Criterion found lower AIC scores when respiration was estimated from air and soil temperatures, than when respiration was estimated from air temperature alone. These AIC scores indicate that model quality is improved by the inclusion of soil temperature, despite the concurrent increase in model complexity."

2. a) *My second top-level concern surrounds the parameter estimation design (section 2.1). The respiration (R) parameter optimization is performed separately from the photosynthesis (GEE) parameter optimization. It seems to me that estimating both subnivean R as well as GEE from observed NEE uses the NEE observations twice, and is therefore likely to produce overly confident parameter estimations. Because NEE is the small difference between two much larger and highly uncertain fluxes (GEE and R), using the NEE observations in this fashion discounts the possibility of equifinality ([low GEE, low R] and [high GEE, high R] could both produce the same NEE). I believe that a joint parameter optimization (see, e.g., Riccietto et al. (2008), Beer et al. (2010), Hilton et al. (2013)) of the six parameters would be a better approach. In my opinion this experimental design needs to be explained more extensively or revised.*
 b) GEE, growing season respiration and snow season respiration were all separately calculated from distinct portions of EC NEE. Daytime growing season NEE was used to fit GEE parameters, where λ and PAR_0 were jointly optimized. Nighttime growing season NEE was used to jointly calculate α and β as the slope and intercept of a linear regression. Snow season NEE was used to jointly calculate α_s and β_s as the slope and intercept of a linear regression. GEE and respiration are calculated separately. This is now better explained in the text.
 c) "The light use efficiency and scaling parameter (λ) was set to be equal to the

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slope from a linear regression of PolarVPRM GEE vs daytime growing season NEE, and was jointly optimized with PAR_0 ."

2.2 Specific comments

1. a) *Regarding the statement "Large uncertainties presently exist in model estimates of high-latitude NEE (Fisher et al., 2014), resulting in diverging estimates by process-based models regarding whether North America is a carbon source or sink (Huntzinger et al., 2012)." (P 980 L 26 to P 981 L 3): Huntzinger et al.(2012) place the vast majority of the uncertainty in North American NEP in the United States (see fig 2A), well south of this study's domain. Hilton et al. (2014) diagnose NEE uncertainty similarly (see fig 14) using the VPRM. If most of the uncertainty in NEE is below the USA-Canada border, then how can the net carbon balance of the continent depend on whether the high latitudes are a source or sink?*
b) The introduction has been edited to remove the reference to Huntzinger's work.
c) "Large uncertainties presently exist in process-based model estimates of high-latitude North American NEE (Fisher et al., 2014), and limit understanding and monitoring of recent changes in the polar carbon cycle."
2. a) *"...little inter-site variability in parameters (Loranty et al., 2011) have indicated the tremendous potential that exists for accurate estimates of regional-scale Arctic NEE to be modeled from satellite observations." (P 981 L 6-8): Loranty et al.(2011) consider arctic tundra, a much smaller domain than this study's domain of north of 55 degrees N latitude. Recent work (e.g. Reichstein et al. (2014)) call into question the ability of plant functional types to categorize model parameters, and Hilton et al.(2013) found little separation of VPRM parameters by PFT. Would a different partitioning for parameterization be better in the non-tundra portions of the North American high latitude (NAHL) domain?*

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b) Although the vegetation classes from the CAVM and SYNMAP products are based exclusively on vegetation types, previous application of Levene's Test have indicated that these vegetation classes split the circumpolar region into groups which have heteroscedastic distributions of snow water equivalent, and growing-season soil moisture, vegetation opacity, and air temperature (Luus et al., 2013b). It would therefore be expected that the classes used capture the different influences of environmental conditions on NEE.

However, even within these very different vegetation classes, the optimal parameters found were similar between classes. I believe that this is because the parameters in VPRM (temperature vs respiration, GEE vs LUE/PAR) are more universal than those in process-based models, and this is what increases accuracy in regional-scale predictions using a simple approach.

I think it is likely that process-based models could benefit more from the application of trait-based approaches than simple data-driven approaches. It is also unclear to me how a plant trait-based approach could be used to estimate NEE regionally over mixed plant types, especially since most EC observations are collected over different combinations of plant species with differing traits without a much denser network of EC observations. At this point, I think the best strategy is the one employed, which relies on the differentiation of large regions into groupings which have different values of snow and growing season characteristics known to influence NEE.

3. a) *P 982 eq (4): Tmin and Tmax are not defined. Are their definitions the same as Mahadevan (2008)? Are their values taken from literature, and if so, for the same reasons?*
b) Yes, Tmin, Topt and Tmax are the same as in Mahadevan (2008), and the values are not optimized for each vegetation class for the same reasons as described by Mahadevan. Mahadevan's values were used for non-arctic vegetation classes, and for all vegetation types, Tmin=0C and Tmax=40C. Topt was set us-

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ing approximations of values found in literature.

c) "As in Mahadevan et al. (2008), $T_{max}=40^{\circ}\text{C}$ and $T_{min}=0^{\circ}\text{C}$ for all vegetation classes, and $T_{opt}=20^{\circ}\text{C}$ over non-arctic vegetation classes. $T_{opt}=15^{\circ}\text{C}$ over shrub tundra and graminoid tundra, as according to e.g. Tieszen (1973); Chapin III (1983). For barren/wetland regions (which include the Canadian High Arctic), a lower $T_{opt}=10^{\circ}\text{C}$ was selected. Plots of air temperature and growing season NEE at calibration sites were then checked to ensure these values appeared reasonable, but no optimization took place, to avoid parameter correlation and instability (Mahadevan et al., 2008). "

4. a) *P 985 L 20-21: "have heterogeneous distributions in snow accumulation, and in growing season drivers of NEE" – what does "heterogeneous distributions" mean? That different vegetation classes are mutually distinguishable by snow accumulation or drivers of NEE?*
 - b) In Luus et al. (2013b), Levene's Test indicated that the population variances of each of the four variables (snow accumulation, air temperature, vegetation opacity, soil moisture) are not equal, across seven groups created by the CAVM-SYNMAP vegetation classes. In other words, the vegetation classes provided split the pan-Arctic region into 7 groups, each of which have distinct populations in terms of all of their snow and growing season characteristics, which influence NEE.
 - c) "Levene's test indicated that these seven vegetation classes have heteroscedastic distributions of passive microwave derived snow water equivalent, and passive microwave derived estimates of growing season NEE drivers (soil moisture, air temperature, and vegetation opacity)."
5. a) *"The minimum, optimum, and maximum temperatures for photosynthesis were evaluated from the meteorological and eddy covariance observations gathered at calibration sites." (P 989 L 5-7): Does this refer to Tmin, Tmax, and Topt from equation 4? Mahadevan et al.(2008) state (section 2.1 paragraph 12) that set-*

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ting these parameters by optimizing to EC data will be unstable with respect to PAR_0 : "Since temperature and PAR are correlated on a daily basis, inclusion of T_{scale} in equation (5) modifies values of PAR_0 inferred from tower flux data. Moreover, were the parameters T_{min} , T_{max} , and T_{opt} in equation (6) to be fit to eddy flux data along with the respiration equation (below) and PAR_0 , parameter values would be unstable because of correlation between the parameters; therefore T_{min} , T_{max} , and T_{opt} were fixed at literature values." Please address this methodology choice.

b) Thank you for pointing out that more information must be provided to clarify the methodology used to select T_{min} , T_{opt} and T_{max} , as well as the values used, so that it is clear that no optimization was used. Accordingly, the T_{min} , T_{opt} , and T_{max} values selected are described in the model structure rather than in the section on model calibration, as these were not tuned in any way.

c) "As in Mahadevan et al. (2008), $T_{max}=40^{\circ}\text{C}$ and $T_{min}=0^{\circ}\text{C}$ for all vegetation classes, and $T_{opt}=20^{\circ}\text{C}$ over non-arctic vegetation classes. For barren/wetland regions (which include the Canadian High Arctic), a $T_{opt}=10^{\circ}\text{C}$, whereas $T_{opt}=15^{\circ}\text{C}$ over shrub tundra and graminoid tundra, as according to e.g. Tieszen (1973); Chapin III (1983). Plots of air temperature and growing season NEE at calibration sites were then checked to ensure these values appeared reasonable, but no optimization took place, to avoid correlation and parameter instability (Mahadevan et al., 2008)."

6. a) *p 988 L 25: "No gap filling was carried out for any of the EC measurements...": This is an excellent choice in this context.*
 - b) Thank you.
7. a) *P 989 L10: "observed GEE": GEE cannot be observed because it is confounded by respiration. Please explain more fully.*
 - b) Yes, excellent point.
 - c) "The light use efficiency and scaling parameter (λ) was set to be equal to the

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slope from a linear regression of PolarVPRM GEE vs daytime growing season NEE, and was jointly optimized with PAR_0 ”

8. a) *P 991 L 20: Does "standard calibration parameters" mean the Mahadevan et al.(2008) values?*
 - b) The standard calibration parameters are those which were set using observations from Imnavait and Barrow. This was ambiguous in the text previously, and has been greatly clarified.
 - c) “Typically, model runs rely on using parameters fitted at the calibration sites (Ivotuk and Atqasuk, respectively). Biases occurring due to mis-parametrization were assessed by first fitting all parameters using EC and meteorological observations from the validation sites (Im & Ba), then comparing model NEE generated using calibration-site parameters (IV & AT), to model NEE generated using site-specific parameters (from Im & Ba, respectively).”
9. a) *P 992 L 19: "Visual examination of these plots": which plots? This will be easier to read if figure numbers are provided explicitly.*
 - b) A mention of the figure number has been explicitly provided on page 992 l 19.
 - c) “Visual examination of Fig. 5, showing monthly average NEE for each model, provided insights into differences in high-latitude carbon cycling estimated by these models.”
10. a) *section 2.5: The text discusses the figures ("were first examined by plotting total CO2 exchange of high-latitude North America", "Trends over time were examined first for each year and each vegetation class, and then pixel-by-pixel across the entire model domain.") but no figure numbers are provided.*
 - b) In the methodology, no figure numbers had previously been provided. All figures were mentioned and referenced whenever discussed later in the text.
 - c) Figures 4–10 are now also referenced in the methodology. in the methodology.
11. a) *P 995 L20 and figure 2: I am having a hard time interpreting the cumulative*
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biases in units of tons carbon per hectare. Please revise the text and figure to use a more conventional unit such as g C m-2. This would allow readers to place the values in context with other published studies (e.g. Huntzinger et al.(2012), Beer et al.(2010)).

c) Figure 2 now shows cumulative biases in g C m-2 rather than t C ha-1, and results are also discussed in gC m-2.

12. a) *P 995 L 25-27: "At Atqasuk and Ivotuk, lambda was set to 0.15 and 0.04, respectively. When the optimal values for lambda were calculated for Barrow and Imnavait, values of 0.29 and 0.34 were identified.": In figure 1 Atqasuk and Ivotuk are calibration sites and Barrow and Imnavait are validation sites. It seems to me the lambda values should be "calculated" at the calibration sites and "set" at the validation sites. Please clarify this text.*
 - b) Yes, model runs at the regional scale all relied on using parameters which had been fitted using EC and meteorological observations from one site per PFT (Daring Lake, Imnavait, and Atqasuk. This portion of text describes results from the portion of the error analysis, which involved fitting model parameters to validation site EC and meteorological observations, and running the model with both the validation-site and calibration-site parameters in order to identify the portion of error due to misparametrization. This is now more clearly stated in both the methodology and results.
 - c) Methodology: “Typically, model runs rely on using parameters fitted at the calibration sites (Ivotuk and Atqasuk, respectively). Biases occurring due to mis-parametrization were assessed by first fitting all parameters using EC and meteorological observations from the validation sites (Im & Ba), then comparing model NEE generated using calibration-site parameters (IV & AT), to model NEE generated using site-specific parameters (from Im & Ba, respectively).” Results: “At the calibration sites, Atqasuk (AT) and Ivotuk (IV), λ values of 0.15 and 0.04 were identified as being optimal values for barren/wetland regions and graminoid tun-

dra sites, respectively. When optimal λ were instead calculated using EC NEE from validation sites (Ba and Im), these yielded values of 0.29 and 0.34, respectively. These differences in optimal parameter values are caused by vegetation at the calibration sites (AT and IV) having a diminished photosynthetic response to light, especially at low light values, relative to plants at validation sites (Ba and Im). The use of sub-optimal λ values (calculated from AT and IV) in estimates of NEE at validation sites (Ba and Im) caused PolarVPRM to underestimate GEE, resulting in a bias in model estimates of NEE."

13. a) *"Furthermore, by calculating snow and growing season respiration separately according to air or soil temperature, accuracy of snow season estimates improved. PolarVPRM estimates of mean three-hourly and monthly NEE were therefore found to be in better agreement with EC NEE than mean three hourly and monthly estimates of NEE generated by CarbonTracker and FLUXNET Multi-Tree Ensemble, respectively." (P 1001 L11-15): This statement is very clear and concise. I found these ideas drowned in detail and thus difficult to glean from the results and discussion section. I think the paper would benefit a lot from a similar summary both in the abstract and early in the results and discussions.*
 b) Thanks, the clarity is improved by highlighting this finding in the abstract and results sections.
 c) Abstract: "PolarVPRM simulates NEE using polar-specific vegetation classes, and by representing high-latitude influences on NEE, such as the influence of soil temperature on subnivean respiration."
 "Comparisons of EC NEE to NEE from three models indicated that PolarVPRM displayed similar or better statistical agreement with eddy covariance observations than existing models showed."
 Results section 3.3 now begins with: "PolarVPRM shows closer agreement with EC NEE from five Arctic sites, than FLUXNET MTE shows against the same five sites (Table 5), indicating that PolarVPRM provides an improved data-driven

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approach for estimating regional-scale Arctic NEE. When three-hourly, daily and monthly averages of PolarVPRM and CarbonTracker were compared to EC NEE from five sites at same timescales, PolarVPRM had the lowest mean RMSEs for all timescales, and lower MBEs at monthly timescales, but larger MBEs at daily and three-hourly timescales. PolarVPRM therefore provides estimates of NEE which show similar or improved realism relative to EC NEE, using a simpler framework than CarbonTracker."

14. a) *I commend the authors for making their model results and code publicly available (P 1002 L 5-7) . This is important and still all too rare.*

2.3 Technical corrections

1. a) *p 983 L 22: The abbreviation "NAHL" is used a number of times but not defined until p 988 L 9.*
 b) Thanks.
 c) NAHL is now defined in the introduction, and methodology.
2. a) *p 982 L 3-4: "these allow PolarVPRM to generate accurate estimates" should be changed to "these allow PolarVPRM to generate more accurate estimates"*
 c) Changed, as suggested.
3. a) *p 991 L 11: EC "observation" should be "observations"*
 c) Fixed.
4. a) *Table 2: Shortwave radiation is listed twice, once with units of Kelvins and once with units of W m-2. Maybe the second entry should be soil T, not radiation?*
 b) Yes, thanks.
 c) Changed to soil T.

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