

Dear Editors and Referees,

Thank you for providing an insightful, constructive and thorough review.

The process of completing the suggested revisions has provided an improved manuscript, as detailed in the responses below, and as indicated in the manuscript found further below, which tracks all recent insertions and deletions made.

Please feel free to refer to the updated manuscript (attached separately) when evaluating the quality of the revised manuscript.

Thank you again,

Kristina Luus

Final Author Comments

(same as posted on the GMDD interactive discussion on April 28, 2015)

All comments and remarks from Referees are provided (a), followed by author responses (b), and changes made to the manuscript (c).

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.*
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 $T_{opt}=10^{\circ}\text{C}$, 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).”

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 diurnal 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 seasonal 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. However, 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 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 “accuracy 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 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 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)

$$R = \begin{cases} \alpha \cdot T_{\text{air}} + \beta : & \text{SCA} < 50 \% \\ \alpha_s \cdot T_{\text{soil}} + \beta_s : & \text{SCA} \geq 50 \% \end{cases} \quad (1)$$

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 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*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*GEE over time, plotted on the same axes, which is a very nice improvement over the previous display.

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 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°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 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., Ricciutto 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 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, than 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 (Lorant 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): Lorant 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?*

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 snow and growing season characteristics.

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 using 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 setting 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 Tmin, Tmax, and Topt 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 Tmin, Tmax, and Topt 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 Tmin, Topt and Tmax, as well as the values used, so that it is clear that no optimization was used. Accordingly, the Tmin, Topt, and Tmax 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 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 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 mis-parametrization. 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 tundra 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 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.

References

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- Lin, J., Pejam, M., Chan, E., Wofsy, S., Gottlieb, E., Margolis, H., and McCaughey, J.: Attributing uncertainties in simulated biospheric carbon fluxes to different error sources, *Global Biogeochem. Cy.*, 25, GB2018, doi:10.1029/2010GB003884, 2011.
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The Polar Vegetation Photosynthesis and Respiration Model (PolarVPRM): a parsimonious, satellite data-driven model of high-latitude CO₂ exchange

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Abstract

We introduce the Polar Vegetation Photosynthesis and Respiration Model (PolarVPRM), a remote-sensing based approach for generating accurate, high resolution ($\geq 1 \text{ km}^2$, three-hourly) estimates of net ecosystem CO_2 exchange (NEE). 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. We present a description, validation, and error analysis (first-order Taylor expansion) of PolarVPRM, followed by an examination of per-pixel trends (2001–2012) in model output for the North American terrestrial region north of 55° N . PolarVPRM was validated against eddy covariance (EC) observations from nine North American sites, of which three were used in model calibration. ~~PolarVPRM performed well over all sites. Model intercomparisons~~ Comparisons of EC NEE to NEE from three models indicated that PolarVPRM ~~showed slightly better displayed similar or better statistical~~ agreement with eddy covariance observations ~~relative to existing models than existing models showed~~. Trend analysis (2001–2012) indicated that warming air temperatures and drought stress in forests increased growing season rates of respiration, and decreased rates of net carbon uptake by vegetation when air temperatures exceeded optimal temperatures for photosynthesis. Concurrent increases in growing season length at Arctic tundra sites allowed increases in photosynthetic uptake over time by tundra vegetation. PolarVPRM estimated that the North American high-latitude region changed from a carbon source (2001–2004) to sink (2005–2010) to source (2011–2012) in response to changing environmental conditions.

1 Introduction

High-latitude permafrost regions contain 1400 to 1850 Gt of soil ~~organic~~-carbon (McGuire et al., 2010), ~~enough to double or triple atmospheric CO_2 concentrations if released entirely to more than twice the amount of carbon presently in~~ the atmosphere. Positive feedbacks between ~~the Arctic carbon cycle and the climate system~~ warming Arctic temperatures

and carbon efflux from thawing permafrost and are therefore likely to have an important role in determining the magnitude of future climate change (Schaefer et al., 2011). Large uncertainties presently exist in process-based model estimates of high-latitude North American NEE (Fisher et al., 2014), ~~resulting in diverging estimates by process-based models regarding whether North America is a carbon source or sink~~ and limit understanding and monitoring of recent changes in the polar carbon cycle.

Simultaneously, recent successes in generating site-level data-driven estimates of net ecosystem CO₂ exchange (NEE) at Arctic sites (e.g. Shaver et al., 2007, 2013; Stoy et al., 2009) with little inter-site variability in parameters (Lorantý et al., 2011) have indicated the tremendous potential that exists for accurate estimates of regional-scale Arctic NEE to be modeled from satellite observations.

In this article, we describe, validate, and examine output from the newly developed Polar Vegetation Photosynthesis and Respiration Model (PolarVPRM). PolarVPRM is an arctic-specific remote-sensing based model which accurately estimates high-latitude net ecosystem CO₂ exchange (NEE) at a fine resolution (three-hourly, $\geq 1 \text{ km}^2$). PolarVPRM is presently in active use by the Arctic research community for a range of applications, including as a model structure through which to examine in situ observations of NEE, and as a priori estimates of Alaskan NEE for Lagrangian modeling of aircraft [CO₂] observations (Miller and Dinardo, 2012).

1.1 PolarVPRM formulation

PolarVPRM presents a high-latitude formulation of VPRM (Mahadevan et al., 2008). Both PolarVPRM and VPRM were written in R (R Development Core Team, 2011), and provide straightforward yet effective calculations of terrestrial biospheric carbon exchange from remote-sensing observations. In both VPRM and PolarVPRM, NEE is calculated as the sum of respiration (R) and gross ecosystem exchange (GEE, the light-dependent portion of NEE), using the sign convention where CO₂ uptake through photosynthesis (GEE) is

negative, and CO_2 efflux to the atmosphere (R) is positive.

$$\text{NEE} = \text{GEE} + \text{R} \quad (1)$$

~~VPRM has-~~

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)), in order to ensure suitability for modeling high-latitude NEE. VPRM has previously been applied and validated across the USA and southern Canada (30–56° N) (Mahadevan et al., 2008; Lin et al., 2011). ~~PolarVPRM contains a number of important differences in inputs and model structure relative to VPRM, and these allow PolarVPRM to generate accurate~~, and PolarVPRM is now applied to generate estimates of NEE across high-latitude regions (e.g. north of 55° N).

1.1.1 Gross ecosystem exchange

Gross ecosystem exchange (GEE), or the photosynthetic uptake of C by vegetation, is calculated according to remote-sensing based estimates of incoming shortwave radiation (SW, where $\text{PAR} = 1.98 \times \text{SW}$; Lin et al., 2011), air temperature (T), land surface water index (LSWI) from Moderate Resolution Imaging Spectroradiometer (MODIS) surface reflectance, and estimates of the fraction of PAR absorbed by photosynthetically active vegetation ($\text{FAPAR}_{\text{PAV}}$), as estimated from the MODIS Enhanced Vegetation Index (EVI).

In Arctic tundra regions, GEE is therefore implicitly limited during the snow season, when EVI is decreased, suggesting that negligible amounts of photosynthetically active vegetation persist above the snow surface. Similarly, GEE can be limited when air temperatures are suboptimal, or when vegetation is at an underdeveloped phenological stage. These limitations are implemented through use of dimensionless scaling variables T_{scale} and P_{scale} , respectively, that both range in value from 0 to 1 (optimal).

LSWI_{max} refers to the maximum annual pixel-specific LSWI value. As in Mahadevan et al. (2008), $T_{\text{max}}=40^\circ \text{C}$ and $T_{\text{min}}=0^\circ \text{C}$ for all vegetation classes, and $T_{\text{opt}}=20^\circ \text{C}$ 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 that these values appeared reasonable, but no optimization took place, to avoid correlation and instability of parameters (Mahadevan et al., 2008). λ refers theoretically to the maximum light use efficiency, or quantum yield, at low light levels, but functions in practice as a combined LUE and scaling parameter. PAR_0 is the half-saturation value of PAR (Mahadevan et al., 2008; Lin et al., 2011).

$$P_{scale} = \frac{1 + LSWI}{2} \quad (2)$$

$$W_{scale} = \frac{1 + LSWI}{1 + LSWI_{max}} \quad (3)$$

$$T_{scale} = \frac{(T - T_{min})(T - T_{max})}{(T - T_{min})(T - T_{max}) - (T - T_{opt})^2} \quad (4)$$

$$GEE = -1 \cdot (\lambda \cdot T_{scale} \cdot W_{scale} \cdot P_{scale}) \cdot FAPAR_{PAV} \cdot \frac{1}{1 + \frac{PAR}{PAR_0}} \cdot PAR \quad (5)$$

Land surface water is implemented as a limitation on GEE (W_{scale}) for forested regions north of 55°N , just as in VPRM. However, water availability does not play a clear role in determining Arctic plant productivity (Oberbauer and Miller, 1979; Chapin III and Shaver, 1985; Shaver et al., 1986; Johnson and Caldwell, 1975) due to the unique prevailing environmental conditions. In wetland regions, water can both stimulate and limit plant productivity. Snowmelt provides a large portion of annual precipitation to Arctic regions, and the high humidity of growing season conditions limits water loss. Water tables are above or at the ground surface in moist/wet tundra ecosystems, and beneath or at the rooting level in shrub/dry tundra (Chapin III et al., 2000). Furthermore, permafrost both limits percolation past the rooting depth, and provides an added input of water to plant roots throughout the growing season (Oberbauer and Dawson, 1992). In low Arctic regions, water availability is

therefore not directly associated with plant productivity (Oberbauer and Miller, 1979; Miller, 2006; Chapin III and Shaver, 1985).

In polar desert regions, surface drying can occur despite ongoing saturation of sub-surface soils, and surface drying therefore has little biological influence on plant productivity (Gold and Bliss, 1995). Water does have an indirect influence in determining Arctic vegetation species distributions due to its role in germination (Bliss, 1958); however, in PolarVPRM, Arctic tundra vegetation remains within the same allocated vegetation class (i.e. graminoid tundra, shrub tundra, or barren/wetland) throughout model runs (< 15 years). W_{scale} is therefore always set to 1 for regions with tundra vegetation, and is calculated according to LSWI in forested areas of NAHL.

1.1.2 Respiration

PolarVPRM uses remote-sensing observations to represent high-latitude (HL) specific drivers of NEE, as observed in recent in situ studies. A central source of uncertainty in estimates of HL NEE involves the characterization of snow season NEE (Belshe et al., 2013), as subnivean respiration persists throughout the snow season despite very low (-25°C) temperatures (Panikov et al., 2006). Arctic field studies have shown that a large portion of annual carbon efflux can occur during the snow season (Aurela et al., 2004; Sullivan et al., 2008; Elberling and Brandt, 2003), and that the timing and magnitude of NEE are influenced by snowpack dynamics (Larsen et al., 2007; Walker et al., 1999; Morgner et al., 2010). During the snow season, the low thermal conductivity of an overlying snowpack (e.g. $0.06 \text{ W (m}^{\circ}\text{C)}^{-1}$ Sturm, 1992) substantially decouples Arctic soil and air temperatures (e.g. by $10\text{--}40^{\circ}\text{C}$ (Zimov et al., 1993), or by $15\text{--}20^{\circ}\text{C}$ Olsson et al., 2003). Rates of subnivean respiration are therefore driven primarily by soil temperature rather than air temperature (Grogan and Jonasson, 2006; Sullivan et al., 2008; Morgner et al., 2010). An opportunity therefore exists to improve model estimates of HL NEE by integrating remote sensing observations of snow (Luus et al., 2013c).

Accuracy in estimates of Arctic NEE throughout the snow and growing seasons is maximized by first demarcating the snow and growing seasons according to Moderate Resolu-

tion Imaging Spectroradiometer (MODIS) observations of fractional snow cover area (SCA) (Appendix A). Snow season ($SCA \geq 50\%$) respiration is then calculated as a linear function of soil temperature, and growing season respiration ($SCA < 50\%$) is calculated as a piecewise linear function of air temperature:

$$R = \text{SCA} < 50: \begin{cases} \alpha \cdot T_{\text{air}} + \beta_{\text{SCA}}: & \text{SCA} < 50\% \\ \alpha_s \cdot T_{\text{soil}} + \beta_s: & \text{SCA} \geq 50\% \end{cases} \quad (6)$$

Previous investigations indicated that filtered MODIS estimates of SCA agreed well with in situ observations of SCA, and that high-latitude respiration is best captured using this approach, which outperforms Q10 and exponential equations as well as formulations using only either soil or air temperatures (Luus et al., 2013a). [Calculating subnivean respiration from soil temperature and growing season 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)

1.1.3 PolarVPRM parameterization by vegetation class

High-latitude vegetation is highly heterogeneous, resulting in large variability in NEE and its drivers by vegetation class (Humphreys and Lafleur, 2011; Elberling, 2007). PolarVPRM therefore separates high-latitude vegetation into seven classes using a combination of the Synergistic Land Cover Product (SYNMAP) (Jung et al., 2006) and the Circumpolar Arctic Vegetation Map (CAVM) (Walker et al., 2005) (Table 1). CAVM is available only above the northernmost treeline, whereas SYNMAP is available globally. CAVM estimates are therefore used wherever available, and SYNMAP estimates are used to classify vegetation south of the CAVM treeline. The CAVM and SYNMAP vegetation classification is available at a $1 \text{ km} \times 1 \text{ km}$ resolution. PolarVPRM estimates can likewise be generate at all resolution $\geq 1 \text{ km}^2$.

[Statistical analysis has previously been applied to examine how well the seven vegetation classes in Table 1 divide the pan-Arctic region. 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), according to (Luus et al., 2013b)

The North American high-latitude (NAHL) spatial resolution selected for this project is $1/6^\circ \times 1/4^\circ$ (latitude \times longitude), and so vegetation classes is regridded accordingly. Each pixel is characterized by its fractional cover by one or more vegetation classes, and by its fractional water/glacier cover. NEE is calculated separately for each vegetation class, and total NEE for each pixel is calculated by multiplying the NEE for each vegetation class by its fractional cover.

~~Statistical analysis has previously been applied to examine how well the seven vegetation classes in Table 1 divide the pan-Arctic region. Remote sensing based statistical analysis indicated that these seven vegetation classes have heterogeneous distributions in snow accumulation, and in growing season drivers of NEE-~~

~~Each vegetation class contains six parameters which are set according to~~ Six separate parameters are used in the calculation of NEE across each vegetation class. All parameters are set empirically from associations found between meteorological and eddy covariance (EC) tower observations ~~from calibration sites at one calibration site per vegetation class.~~ Two parameters are used to calculate GEE (Eq. 5), and four parameters are used to calculate respiration (Eq. 6):

- PAR_0 ~~, which represents~~ describes the sensitivity of photosynthetic uptake to the quantity of incoming shortwave radiation
- λ ~~, which~~ represents light use efficiency of vegetation, and also acts as a scaling parameter
- α and β ~~, regression coefficients describing~~ regression coefficients describe the linear association between ~~air temperature and~~ growing season respiration $(R = \alpha T_{air} + \beta)$ and air temperature

- α_s and β_s ; ~~regression coefficients describing~~ regression coefficients describe the linear association between soil temperature and snow season respiration
 ~~$(R = \alpha_s T_{\text{soil}} + \beta_s)$~~

1.1.4 PolarVPRM inputs

PolarVPRM remote sensing observations of the land surface were acquired from the Moderate-resolution Imaging Spectroradiometer (MODIS), and meteorological observations were acquired from the North American Regional Reanalysis (NARR), at the native spatial and temporal resolutions summarized in Table 2. All inputs were then regridded to the PolarVPRM spatial domain (NAHL, $1/6^\circ \times 1/4^\circ$ latitude \times longitude) using bilinear interpolation in R. MODIS was linearly interpolated to three-hourly timesteps. PolarVPRM was run at NARR's native temporal resolution (three-hourly), although it could easily be run at a ~~much finer~~ finer spatiotemporal resolution with higher resolution ~~meteorological inputs.~~ MODIS was linearly interpolated to three-hourly timesteps. inputs. For a complete discussion of the changes made to ~~the MODIS model~~ inputs, and ~~of the reason why these reasons~~ why specific meteorological products were selected, please refer to Appendix A.

1.2 Calibration and validation sites

PolarVPRM was calibrated and validated using standard meteorological observations and open-path eddy covariance measurements of NEE collected at HL North American sites (Table 3; Fig. 1).

Atqasuk (AT) and Barrow (Ba) are both located on the North Slope of Alaska, and were designated as paired calibration/validation sites representing barren/wetland vegetation in PolarVPRM. Field observations at the main Barrow EC site have indicated full flooding following snowmelt, with vegetation that consists mainly of wet sedges, moss, lichens and grasses (Oechel et al., 1995; Harazono et al., 2003). The Atqasuk EC site is located \approx 100 km south of Barrow, and is both warmer and drier than the Barrow site. The predominant vegetation at Atqasuk is moist-wet sedge, underlain by wet, acidic soils (Kwon et al., 2006).

Due to the similarity of these sites, they have previously acted as paired sites in studies of the Arctic carbon cycle (Hollister et al., 2005; Huemmrich et al., 2010).

Imnavait (Im) and Ivotuk (IV) are moist tussock tundra sites which were paired for calibration/validation, and represent the graminoid tundra vegetation class in PolarVPRM. Imnavait is located in the foothills north of the Brooks Range, in a region largely dominated by moist acidic tussock tundra (Euskirchen et al., 2012). Ivotuk is a moist acidic tussock tundra site located ≈ 200 km south of Atkasuk (Thompson et al., 2006; Laskowski, 2010), and Imnavait is located ≈ 200 km east of Ivotuk. The similarities in predominant vegetation, and geographical proximity, allowed these two sites to be paired.

The main Daring Lake (DL) EC site is located in a region of mixed tundra, in Canada's Northwest Territories (Lafleur and Humphreys, 2008; Humphreys and Lafleur, 2011). Observations from this site were used to calibrate the shrub tundra vegetation class. Since no other year-round EC observations were available at NAHL sites designated as shrub tundra from 2001–2012, validation for this class consisted of characterizing model performance over years which were not used for validation, and by describing the performance of this parameterization in describing NEE at Ivotuk (IV).

Meteorological and EC observations were collected during a portion of the 2008 growing season by (Lafleur et al., 2012) at Canadian high Arctic sites: Lake Hazen (lh), Cape Bounty (cb), Pond Inlet (pi), Iqaluit (iq). Observations from these sites were used as model validation for the graminoid and shrub tundra classes.

2 Methodology

Briefly, PolarVPRM estimates of three-hourly NEE were validated against observations from nine North American sites, and a detailed error attribution was then conducted using observations from two validation EC tower sites. Output from PolarVPRM and two existing models (CarbonTracker and FLUXNET Multi-Tree Ensemble) ~~are~~were then compared, relative to EC observations. Changes over time (2001–2012) in PolarVPRM estimates of carbon cycling were then examined at various spatial scales across the entire high-latitude (north of

55° N) North American terrestrial region, hereafter referred to as NAHL, for the 2001–2012 time period.

2.1 Calibration

Sites with year-round eddy covariance observations (Fig. 1) were first described using the combined CAVM and SYNMAP classification (Table 1), and then paired. The CAVM and SYNMAP combined classification was specifically designed to allow for ecological differences resulting in varying flux drivers to be well represented, while ensuring that no category would be created that could not be parameterized using the existing eddy covariance infrastructure. If more year-round flux towers existed, then further distinctions could have been made between vegetation classes (e.g. barren/wetland).

Atqasuk, Ivotuk and Daring Lake were then selected as the calibration sites because they alone shared year-round observations during a single common year (2005). Parameter values for PolarVPRM's three Arctic tundra vegetation classes were then set using half-hourly observations from EC and meteorological towers collected at Daring Lake, (Lafleur and Humphreys, 2008; Humphreys and Lafleur, 2011), Ivotuk (Laskowski, 2010), and Atqasuk (Laskowski, 2010) (Fig. 1). In all cases, observations of NEE were filtered only to remove observations collected during instrument malfunction or when frictional velocity was low ($u^* < 0.2$) (Goulden et al., 1996). No gap filling was carried out for any of the EC measurements, as gap filling requires the application of another model and therefore does not represent a direct measurement of CO_2 flux (Barr et al., 2004).

Respiration parameters were set using simple linear ~~regression~~regressions of air temperature and nighttime NEE (α and β), or subnivean soil temperature and snow season NEE (α_s and β_s). ~~The minimum, optimum, and maximum temperatures for photosynthesis were evaluated from the meteorological and eddy covariance observations gathered at calibration sites.~~ PAR_0 was set according to a non-linear least squares fit of PAR and GEE, using the `nls` function in R (R Development Core Team, 2011).

The light use efficiency and scaling parameter (λ) was set to be equal to the slope from a linear regression of ~~model vs observed~~ PolarVPRM GEE vs daytime growing season GEE NEE

These parameters remained unchanged for all simulations, and were applied to generate regional estimates, as well as estimates at calibration and validation sites. Parameters for vegetation classes south of the treeline were set according to the VPRM parameterizations (Mahadevan et al., 2008). Please refer to (Mahadevan et al., 2008) for a detailed description of these study sites, the calibration approach used, and results indicating good predictions of monthly NEE over forested calibration sites, and their respective cross-validation sites.

Following model calibration at high-latitude sites, PolarVPRM estimates of GEE, respiration and NEE were generated for the entire North American region north of 55° N for years 2001–2012 at a three-hourly timestep and a spatial resolution of $1/6^\circ \times 1/4^\circ$ (latitude \times longitude), ~~at a three-hourly timestep for years 2001–2012~~. The output from these simulations was used to conduct error analysis, validation, model intercomparisons, and trend analysis.

2.2 Validation

Validation consisted of examining model performance both over paired calibration/validation sites (AT, Ba, IV, Im), as well as growing season validation sites (lh, cb, pi, iq, ch). These sites capture a wide variety of vegetation types and regions of the North American arctic, especially in light of the small total number of sites in this region with continuous year-round observations during the MODIS era (2000–).

Model evaluation consisted of examining the Mean Bias Error (MBE) and Root Mean Squared Error (RMSE) between PolarVPRM estimates of mean three-hourly, daily and monthly average NEE (pred_i), and EC measurements of NEE (obs_i) at matching temporal resolutions:

$$\text{MBE} = n^{-1} \sum_{i=1}^n \text{pred}_i - \text{obs}_i \quad (7)$$

$$\text{RMSE} = \left[n^{-1} \sum_{i=1}^n |\text{pred}_i - \text{obs}_i|^2 \right]^{1/2} \quad (8)$$

Validation was conducted against 2005 EC observations at the three calibration sites (DL, AT, IV), and against observations from 2008 and 2001 at Im and Ba, respectively. 2008 and 2001 were selected as these were the closest years to 2005 for which year-round observations existed. After error metrics were calculated, plots comparing modeled and observed values of NEE were generated to assist in identifying biases in modeled NEE. Validation was also conducted using observations of NEE collected in July 2008 by (Lafleur et al., 2012) from four Canadian Arctic sites (cb, iq, lh and pi).

Mean daily [values comparisons](#) of NEE were used because of the large number of gaps found in eddy covariance observations, and the decision to not apply any gap-filling approaches to the flux data, as this would then constitute an inter-model comparison rather than a comparison of model estimates against eddy covariance observations. To ensure that these daily flux estimates would not be biased relative to model estimates in situations where more gaps in flux observations occurred at night rather than during the day, model estimates corresponding to time periods with missing observations were not included when calculating mean daily NEE. Validation therefore described the fit between model output, and in situ observations of NEE.

2.3 Error analysis

Due to the simple mathematical formulation of VPRM and PolarVPRM, uncertainties in estimates of NEE can be easily partitioned into systematic versus random errors (Lin et al., 2011). Systematic errors or biases cause model output to be offset in a specific direction, whereas random errors introduce additional and erroneous fluctuations in value. In order to better understand the deviation between PolarVPRM estimates of NEE and EC measurements of NEE, a comprehensive error analysis was completed according to the framework developed by (Lin et al., 2011), which is based on a first-order Taylor expansion.

Within this framework, errors are quantified by examining model estimates against eddy covariance ~~observation~~ observations at two year-round validation sites, Imnavait (Im) and Barrow (Ba), which had not been used in model calibration. Errors are then classified as either systematic or random. Errors are then attributed to input variables and parameters, and their total contributions to uncertainty in estimates of NEE are examined. Biases occurring due to input variables are addressed by comparing inputted shortwave radiation, soil temperature and air temperature, to NARR-derived estimates of these variables, and examining the portion of error in NEE arising from these discrepancies. Typically, model runs rely on using parameters fitted at the calibration sites (Ivotuk and Atqasuk, respectively). Biases occurring due to mis-parametrization ~~are assessed by refitting all parameters at~~ were assessed by first fitting all parameters using EC and meteorological observations from the validation sites ~~, and comparing modeled NEE at the validation sites which is calculated using the standard calibration parameters, to modeled NEE at the validation sites calculated according to the validation site specific parameters (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).~~ Plotting the contribution of each component to model error then allows their relative contributions to be assessed.

2.4 Model inter-comparison

PolarVPRM estimates of NEE were ~~then compared against those generated~~ compared against estimates of NEE by existing models with different formulations, ~~and all~~. All models were compared against EC NEE, which was upsampled from a half-hourly temporal resolution to three-hourly, daily and monthly time periods.

The models selected for inter-comparison were CarbonTracker and FLUXNET Model-Tree Ensemble (MTE). CarbonTracker (Peters et al., 2007) and FLUXNET MTE (Jung et al., 2009) were selected on the basis that both provide estimates of NEE over northern regions, and both use approaches which are different from one another and from PolarVPRM.

CarbonTracker derives estimates of CO₂ surface fluxes by analyzing atmospheric CO₂ observations using a transport model (Transport Model 5, TM5) (Krol et al., 2005) in combination with a land surface biospheric flux model (Carnegie-Ames-Stanford Approach, CASA) (Potter et al., 1993) and fossil fuel inventories. One identified source of uncertainty in CarbonTracker estimates is from measurement errors or biases in CO₂ dry mole fractions (Masarie et al., 2011). FLUXNET MTE generates regional estimates of NEE by first training an ensemble of model trees using EC measurements from FLUXNET sites and inputs from the Lund–Potsdam–Jena managed Land (LPJmL) model (Bondeau et al., 2007), and then upscaling these measurements accordingly. Uncertainty in FLUXNET MTE estimates of NEE has previously been through assessment of GPP simulated by LPJmL (Jung et al., 2009).

Estimates of NEE by PolarVPRM, CarbonTracker and FLUXNET MTE were spatially averaged for the entire terrestrial region north of 55° N at a monthly resolution for each year (2001–2012). Visual examination of ~~these plots~~ Fig. 3, showing monthly average NEE for each model, provided insights into differences in ~~inter-annual variability, and in estimates of the total carbon cycle by all three~~ high-latitude carbon cycling estimated by these models. Further analysis then consisted of creating similar plots examining PolarVPRM and CarbonTracker model output at distinct time slices (Fig. 4), as both of these models are available at a three hourly resolution. In order to create these plots, a distinct time of day was selected for each plot, and model estimates were then spatially averaged over the North American high-latitude domain, and averaged for each month of each year. Analysis of these plots highlighted differences in the representation of diurnal patterns in high-latitude NEE.

PolarVPRM, CarbonTracker and FLUXNET MTE estimates of three-hourly and mean monthly NEE were then compared against three-hourly and monthly observations of NEE available at the PolarVPRM calibration and validation sites for which annual observations were available: Atqasuk, Barrow, Daring Lake, Imnavait and Ivotuk.

2.5 Trends (2001–2012)

Changes over time in the high-latitude carbon cycle were first examined by plotting total CO₂ exchange ~~of high-latitude North America~~ across the North American high-latitude (NAHL) model domain to determine the relative contributions of respiration and photosynthesis (Fig. 5). Although recognized model uncertainties and the impossibility of thoroughly evaluating PolarVPRM performance across the heterogeneous model domain with current infrastructure limit confidence in estimates of the total carbon balance, examination of relative changes in CO₂ exchange over time and its drivers provide insights into responses of the high-latitude carbon cycle to recent environmental changes.

Trends over time were examined first for each year and each vegetation class, and then pixel-by-pixel across the entire model domain (Figs. 6–10). The non-parametric slope estimator (Sen's slope) (Sen, 1968) was applied to each pixel to determine the trend during the years 2001–2012 of NEE, GEE and respiration. All calculations of Sen's slope values and their significance were conducted in R using the `rkt` package (Marchetto, 2012).

To further understand the specific influences driving these shifts, changes over time in carbon cycle variables and driver data were separately analyzed over the snow season (SS) and growing season (GS). These time periods were differentiated using MODIS MOD10A2 snow cover area (SCA), as a previous study indicated that remote-sensing estimates of 50 % SCA can accurately capture the timing of seasonal transitions in the low Arctic (Luus et al., 2013a). Changes over time in model inputs/outputs describing land surface characteristics are therefore described annually, as well as over the snow season (when $SCA \geq 50\%$). Estimates of model variables over the growing season are limited to the portion of the year for which the land surface is snow free and for which vegetation is photosynthetically active ($SCA < 50\%$ AND $GEE < 0$). This was done so that different insights could be gained into annual GEE and respiration, vs. GEE and respiration during the active growing season. The Sen's slope estimates of median changes in carbon cycle and land surface variables over time (2001–2012) were then reported for each pixel in the model domain corresponding to significant (p value < 0.05) change.

3 Results and discussion

3.1 Validation

PolarVPRM three-hourly estimates of NEE showed excellent agreement with ~~observations of NEE acquired three-hourly averaged NEE measured~~ at four Canadian Arctic sites during the 2008 growing season (Lafleur et al., 2012). The mean RMSE across all sites was $0.79 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, and was largest at Iqaluit ($1.01 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) and smallest at Cape Bounty ($0.66 \mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) (Table 4). Although these errors are not negligible, the values are quite low considering the large distances between calibration sites and growing season validation sites (Fig. 1), as well as the large inter-site environmental differences (Lafleur et al., 2012).

A slight negative bias in model estimates was found at two sites (iq and lh), and a slight positive bias was found at the other two sites (cb and pi). Biases in NEE at these sites arose mainly due to biases in NARR shortwave radiation and air temperature. At Lake Hazen, NARR air temperatures were 10°C colder on average than observed air temperatures, leading both photosynthesis and respiration to be underestimated. Furthermore, EVI remained low at Lake Hazen (< 0.1) and Iqaluit (< 0.2) throughout July 2008. Photosynthesis at these sites was therefore underestimated, which caused a slight negative biases in NEE at these sites (lhMBE = -0.39 , iq MBE = -0.15). At Cape Bounty and Pond Inlet, NARR shortwave radiation was substantially larger than observed, such that cb measured PAR $\approx 1.3 \times$ cb NARR SW radiation, and iq measured PAR $\approx 1.6 \times$ iq NARR SW radiation. These biases in shortwave radiation cause overall rates of photosynthesis at these sites to be overestimated, leading to a positive bias in NEE (cb MBE= 0.33 , pi MBE= 0.44). Despite the small biases introduced from meteorological inputs, PolarVPRM performs relatively well at high-latitude, remote growing season validation sites.

3.2 Error analysis

Comparisons of PolarVPRM NEE against observations of NEE at year-round calibration and validation sites indicated that PolarVPRM tended to slightly underestimate net C uptake by vegetation at validation sites (Barrow and Imnavait). The underlying reasons for the bias in net C uptake at year-round validation were addressed through a comprehensive error analysis.

The cumulative monthly bias in PolarVPRM, expressed as the difference between PolarVPRM modeled NEE and observed NEE ($\text{model} - \text{observed}$), is indicated for two validation sites, Barrow and Imnavait in Fig. 2. In this figure, a positive bias in NEE indicates that either respiration was overestimated, or that photosynthetic uptake by vegetation was underestimated. Therefore, according to the sign convention used for NEE, a positive bias in respiration indicate that PolarVPRM overestimated respiration, whereas a positive bias in GEE indicates that PolarVPRM underestimated photosynthetic uptake by vegetation.

Findings from the error analysis indicated that the main sources of error in PolarVPRM estimates of NEE arose from biases in how the associations between PAR and GEE, and between λ and GEE, were parameterized (Fig. 2). NARR air temperature and soil temperature agree closely with observed soil and air temperatures, meaning there is very little bias in estimates of respiration. Small errors in NARR shortwave radiation relative to observations caused small ($< 0.01 < 1 \text{ g C m}^{-2}$) cumulative biases in net C exchange at these validation sites.

At Barrow and Imnavait (Ba and Imnavait (Im)), the amount of carbon taken up through photosynthesis is underestimated due to biases in λ , the light use efficiency and scaling parameter (Eq. 5). The At the calibration sites, Atgasuk (AT) and Ivotuk (IV), λ values of 0.15 and 0.04 were identified as being optimal values for barren/wetland regions and graminoid tundra 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) showed having a diminished photosynthetic response to light, especially at low

light values, relative to plants at validation sites (Ba and Im). ~~At Atqasuk and Ivotuk, λ was set to 0.15 and 0.04, respectively. When the optimal values for~~ The use of sub-optimal λ were calculated for Barrow and Imnavait, values of 0.29 and 0.34 were identified 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.

A recent study by (Dietze et al., 2014) likewise identified misparameterization of light-use efficiency at low light levels to play a central role in biospheric model uncertainties across HL regions of North America. The study indicated that a likely source for misparameterization is due to greater variance in this parameter across high-latitude sites, even when these contain similar biota. Although PolarVPRM calibration and validation sites were paired on the basis of having similar physical and biological characteristics, important differences appear to exist in the drivers of NEE at these sites, which are not captured by PolarVPRM. In order to identify whether the calibration or validation LUE values are more representative across HL tundra sites, a larger network of HL EC towers and measurements of light-response curves using leaf-level observations of gas exchange (Bernacchi et al., 2013) would be required.

A portion of the error observed at Barrow and Imnavait arises due to biases which are not considered in the error analysis framework. The gap between the sum of all biases and the total error is evident at both Barrow and Imnavait (Fig. 2). The error analysis approach used is based on a first-order Taylor expansion, and therefore does not consider second order effects (Lin et al., 2011). As PolarVPRM has a simple model structure, it is likely that a portion of the bias arises due to incomplete characterization of the processes which drive carbon cycling. Future work will consist of further improving the accuracy of PolarVPRM estimates. Spatial heterogeneity in rates of respiration and CO₂ release from permafrost could be better represented by including satellite-derived maps of permafrost information (e.g. Heim et al., 2011). Estimates of PolarVPRM GEE could also be improved in future once capabilities exist to accurately estimate vegetation fluorescence or photosynthetic stress from the Photochemical Reflectance Index (Grace et al., 2007; Hilker et al., 2008) across vast Arctic regions. Overall, although mis-parametrization of λ at the validation sites accounts

for the most significant portion of error at Barrow and Imnavait, a hidden bias in NEE exists that compensates for the bias in λ , resulting in smaller net biases in NEE than would be expected through error decomposition.

3.3 Model inter-comparison

Comparisons of mean monthly NEE by PolarVPRM, CarbonTracker and FLUXNET Model-Tree Ensemble over NAHL indicated that both CarbonTracker and PolarVPRM estimated very low rates of mid-winter respiration, whereas the FLUXNET Model-Tree Ensemble (MTE) showed greater rates of mid-winter respiration (Fig. 3). FLUXNET MTE also estimates greater photosynthetic uptake of carbon by vegetation than the other two models. ~~Comparisons of mean monthly NEE observed at year-round calibration and validation sites to mean monthly NEE from the three models indicated that CarbonTracker and PolarVPRM agreed more closely with field observations than FLUXNET MTE (Table 5). PolarVPRM had lower RMSE values across sites than CarbonTracker, and CarbonTracker had slightly lower MBE values than PolarVPRM.~~ The seasonal cycle and inter-annual variability displayed by PolarVPRM and CarbonTracker are very similar (Fig. 3).

Relative to CarbonTracker, PolarVPRM estimates less carbon to be taken up by vegetation photosynthetically at midday (18:00 UST), and estimates less respiration to occur in the middle of the night during the growing season (06:00 UST) (Fig. 4). However, when three-hourly estimates of NEE by PolarVPRM and CarbonTracker are compared against three-hourly EC measurements of NEE, PolarVPRM is found to have lower ~~error terms~~ RMSE values than CarbonTracker (Table 5). ~~PolarVPRM appears to have lower error terms than CarbonTracker mainly~~

PolarVPRM may have lower RMSEs than CarbonTracker because CarbonTracker estimates less photosynthesis to occur at 00:00 and 12:00 UST than estimated by PolarVPRM. Arctic regions receive sunlight continuously through the mid-summer season, and Arctic tundra vegetation has been observed to conduct photosynthesis continuously throughout midsummer, despite low light levels and low temperatures found at solar midnight (Tieszen, 1973; Patankar et al., 2013). PolarVPRM's ability to simulate photosynthesis according to

actual light availability at high latitudes therefore allows ~~PolarVPRM's three-hourly~~ estimates of NEE to agree closely with ~~three-hourly~~ averaged EC NEE, especially when considered at monthly intervals. In summary, PolarVPRM provides a simple approach for generating reliable estimates of NEE.

3.4 Regional trends (2001–2012)

~~Estimates~~ Regional trends are examined here for the purpose of examining the direction of potential inter-annual variability, as uncertainties in regional-scale estimates of North American NEE limit the capacity to quantify the high-latitude C balance of this area, or to accurately place error bars on estimates of regional scale net C balances. Model estimates of the mean annual carbon balance of the North American region north of 55° N indicate that this region was likely may have been a carbon source from 2001–2004 and 2010–2012, and a weak carbon sink between 2005–2009 (Fig. 5a). Between 2001–2009, respiration diminished, and then rose again from 2010 onward (Fig. 5b). After 2004, GEE became less negative over time, indicating less CO₂ uptake per year (Fig. 5c). The shift from a carbon sink to source in 2005 was therefore likely mainly due to a decline in respiration, whereas the later shift from a carbon sink to source was due to a decrease in the amount of CO₂ taken up by vegetation through. Respiration changes more than GEE over time, and appears to have a larger role in determining changes over time in NAHL net C uptake than photosynthesis.

Several general tendencies appear when examining monthly average NEE over time (2001–2012) from each PolarVPRM vegetation class (Fig. 6). In 2001–2005, PolarVPRM estimates that high-latitude North America was a carbon source (Fig. 5a) as the source strength of tundra regions exceeded the sink strength of forested regions. Over time (2005–2010), forested regions took up less carbon through photosynthesis year after year (Fig. 6). Graminoid tundra and barren regions continue to function as net carbon sources, and forested regions continue to function as net carbon sinks. Shrub tundra regions appear to be shifting towards becoming carbon sinks because of an increase in the amount of C taken up through photosynthesis. The decrease in respiration observed in (Fig. 5 b) is due largely to a small decrease in snow season respiration. Although this decrease is minor on

a monthly level, its cumulative impact on the carbon balance is substantial. Forests have stronger fluxes than tundra vegetation, and therefore have a greater relative contribution to the North American high-latitude carbon cycle than tundra regions, leading to a net increase in CO₂ efflux from 2007 onward (Fig. 5).

3.5 Per-pixel trends (2001–2012)

Previous studies have described the influence of warming air temperatures on inducing increased rates of net carbon uptake by vegetation near the shrub and tree lines (Hinzman et al., 2005; Tape et al., 2006), and on increasing rates of CO₂ efflux (Schuur et al., 2009; Tarnocai, 2006). Remote sensing studies have found trends towards increased growing season length (Zeng et al., 2011), increased NDVI over tundra regions due to warming (Stow et al., 2004), and diminished NDVI over boreal regions due to reduced rates of photosynthesis (Verbyla, 2008). Since PolarVPRM is driven by remote sensing observations, the effects of these environmental changes for HL carbon cycling can be examined by analyzing trends in PolarVPRM output.

Trends over time in carbon cycle variables were examined for each pixel in NAHL individually using the non-parametric Theil-Sen estimator (Sen's slope). Initial analyses were conducted according to mean annual values of net carbon uptake, NEE, respiration, and GEE (Fig. 7). Visual examination of these plots indicated a net increase in carbon efflux from high-latitude regions, focused mainly in forested regions (Fig. 7a). The observed increase in annual carbon efflux from forested regions over time arises mostly due to a decrease over time in the photosynthetic uptake of carbon (represented by an increase in GEE) (Fig. 7c). Although photosynthetic uptake in parts of northern Alaska and the Yukon increased over time, greater uptake was outweighed by the declines observed over forested regions. The net change in GEE is therefore mainly indicative of diminished sink strength over time. Effluxes of CO₂ from Arctic tundra regions increased over time due to greater rates of respiration (Fig. 7b). Overall, this results in a slight trend toward less net CO₂ uptake across the entire model domain (Fig. 7a), especially from 2005 onward.

The amount of carbon taken up by vegetation through photosynthesis increased over tundra regions, and declined sharply over forest regions (Fig. 7c). When considering trends only over the active growing season (when $GEE < 0$), there was a slight increase in the amount of carbon taken up by North American vegetation during the growing season (Fig. 8a). This discrepancy is due to the inability of model vegetation to conduct photosynthesis when temperatures rise above the maximum air temperatures permitted for photosynthesis, and due to increased drought stress in warm conditions. As air temperatures warm above the physiologically optimal temperatures, and drought stress increases, the capacity for photosynthesis diminishes strongly.

Positive air temperature anomalies and increased drought stress during the growing season therefore limit the total amount of carbon taken up by forest vegetation, while generally, rising EVI (Fig. 8c) and air temperatures (Fig. 8d) increase photosynthetic activity whenever temperatures are not excessively hot. It is also interesting to note that a further consequence of rising air temperatures is a concurrent rise in growing season rates of respiration (Fig. 8b), which seems to partially counteract the increase in photosynthesis observed across the model domain (Fig. 8a).

Cooling trends in snow season NARR T_{air} resulted in colder T_{soil} over time south of the treeline, resulting in diminished respiration, but less change over time was observed in soil and air temperatures north of the treeline (Fig. 9c and d). Recent studies have indicated cooling trends in winter air temperatures over high-latitude regions of North America could be due to trends in the Madden–Julian Oscillation (Yoo et al., 2011), or due to deepened Eurasian snow depth (Cohen et al., 2012). As snow season length also diminishes over time (Fig. 9b), it could be expected that subnivean effluxes of CO_2 would contribute less carbon annually to the atmosphere over time. Only a small decline over time was observed in snow season respiration over forested regions (Fig. 9a). Conversely, diminished snow season length could contribute to the observed rises in growing season respiration (Fig. 8b). The initial decline, and later rise, in respiration are therefore likely to occur due to counteracting trends over time in snow and growing season respiration.

The boreal forest appears to have a dominant role in determining fluxes of CO₂ over North American latitudes north of 55° N. Although photosynthetic uptake in tundra regions increases over time, this is largely outweighed by concurrent rises in respiration due to warming air temperatures. Forest regions are also capable of greater rates of photosynthesis during the active growing season ($GEE < 0$), but carbon uptake is limited due to drought and temperature stress. As a result, reductions over time occur in the amount of carbon taken up by vegetation. Furthermore, although subnivean effluxes of CO₂ diminish over time due to shortened snow seasons and diminished snow season soil temperatures, annual rates of respiration increase over time. PolarVPRM outputs indicate that it is likely that North American HL regions have recently been emitting more CO₂ into the atmosphere in response to warming air temperatures.

4 Conclusions

PolarVPRM provides a remote-sensing based approach for generating high-resolution estimates of NEE using a parsimonious model approach that is specifically adapted for high-latitude regions. The sources of error in PolarVPRM estimates of NEE are well understood. PolarVPRM adequately simulates high-latitude ~~NEE~~ 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, ~~and classifies vegetation using Arctic-specific vegetation classes using shortwave radiation as a driver of GEE~~. Furthermore, ~~by calculating~~ snow and growing season respiration ~~separately are separately calculated~~ according to air or soil temperature, ~~accuracy of which has previously been shown to improve accuracy in~~ 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 of NEE, relative to the standard VPRM framework (Luus et al., 2013a). When PolarVPRM, CarbonTracker, and FLUXNET MTE were all examined against EC NEE averaged over~~

three-hourly, daily and monthly timescales, the smallest RMSE values for each timescale were found in comparisons of PolarVPRM NEE to EC NEE, indicating excellent model performance.

Due to the parsimonious model structure used in PolarVPRM, and the easily describable associations between inputs and outputs, examination of trends in PolarVPRM NEE and its drivers provides insights into how the NAHL carbon cycle may be responding to changing environmental conditions. PolarVPRM estimates of high-latitude (55–83° N) North American NEE showed an increase over time (2007–2012) in net carbon efflux by high-latitude ecosystems, and shifted recently between being a carbon sink (2005–2010), and carbon sink (2001–2004, 2011–2012). Initially, high-latitude regions increased their net uptake of carbon over time (2001–2005) due to an increase in rates of photosynthesis by Arctic vegetation. Subsequently, net carbon efflux from high-latitude regions increased (2011–2012) due to declines in photosynthesis over boreal regions in response to temperature and drought stress. Overall, PolarVPRM indicates that warmer air temperatures are enabling Arctic vegetation to take up more carbon photosynthetically, while simultaneously increasing high-latitude rates of respiration, and diminishing photosynthetic uptake of carbon by boreal vegetation.

Code availability

Model estimates of PolarVPRM NEE, respiration and GEE across North America (north of 55° N) will be made publicly available upon publication of this article. Code will be available by request from kluus@bgc-jena.mpg.de.

Appendix A: MODIS and NARR input data

Several changes were made to the remote-sensing derived input data used by PolarVPRM, relative to VPRM. Firstly, MODIS MOD10A2 observations of fractional snow cover (Hall et al., 1995; Hall and Riggs, 2007; Riggs and Hall, 2011) were included to differentiate snow and growing season respiration. Preliminary assessment indicated that the MOD10A2

Collection 5 fractional snow cover area has false positive and false negative values at high-latitude sites. False negatives in MODIS estimates of fractional snow cover occur when reflectance is very low in winter due to surface features or illumination factors. Omission errors can also arise during snowmelt over terrestrial pixels containing a mix of snow/ice and land, as land can warm up quickly, and be identified as snow-free when it exceeds the algorithm's temperature threshold (> 283 K) (G. Riggs, personal communication, 2012). False positives in MODIS SCA arise when the MODIS cloud mask misses a cloud or the edge of a cloud. Both false positives and false negatives are most common at high-latitude sites, due to the characteristic cloud cover, and low winter solar angles. These errors will be reduced in upcoming versions of MOD10 snow cover area (G. Riggs, personal communication, 2012).

In order to use MOD10A2 observations effectively, some filtering and smoothing techniques were applied to the remote-sensing observations before they were included in PolarVPRM. First, MOD10A2 observations were only used for pixels and time periods where both MOD10A2 and the corresponding surface reflectance observations were flagged as "excellent". Soil temperature masks were also applied to eliminate false positives in mid-summer, and false negatives in mid-winter. Furthermore, since snow melt and snow onset occur rapidly in high-latitude regions, the R_{loess} (local polynomial regression fitting) smoothing algorithm R Development Core Team (2011) was applied to reduce noise in estimates of fractional snow cover, and to allow temporal gap filling for missing observations. When MODIS MOD10A2 observations were corrected using this approach, good agreement was then found between remotely sensed and locally observed fractional snow cover.

The original VPRM calculated LSWI and EVI from MOD09 surface reflectance. However, EVI calculated from MOD09 contained anomalous values at high latitude sites, likely due to the prevalence of cloud cover and snow/ice, which have high reflectance of blue light, and therefore cause atmospheric over-correction. The MOD13 series of products provide more reliable estimates of EVI at high latitude sites, because a backup two-band EVI algorithm is used when blue band reflectance is high Solano et al. (2010). MOD13A1 EVI was therefore included in PolarVPRM instead of estimates of EVI calculated from MOD09A1 surface reflectance.

Meteorological observations from the North American Regional Reanalysis (NARR) were used to drive PolarVPRM. High-latitude meteorological estimates tend to be biased towards overestimating shortwave radiation due to errors in simulating both the amount of cloud cover, as well as the influence of clouds on the surface energy balance Walsh et al. (2009). It was therefore important that meteorological products with the smallest errors possible would be used as inputs to PolarVPRM. The selection process through which NARR was chosen involved comparing two well-established meteorological reanalysis products, NARR Mesinger et al. (2006) and the North American Land Data Assimilation System (NLDAS) Mitchell et al. (2004), to ground-based meteorological observations collected at Daring Lake, NWT Humphreys and Lafleur (2011); Lafleur and Humphreys (2008). Daring Lake was selected as the validation site for these products because it is less likely that the inputs to the NARR and NLDAS data assimilations had been extensively calibrated at Daring Lake, relative to the other sites, which are all Alaskan Ameriflux sites. Comparisons at Daring Lake indicated that although both NARR and NLDAS overestimated air temperatures at 2 m above ground (T_{air}) and downward shortwave radiation, these overestimates were much smaller in NARR. Furthermore, NARR has been used and validated in a number of high-latitude studies (e.g. Langlois et al., 2012; Miller et al., 2014).

Errors and biases in NARR meteorological estimates at all year-round calibration and validation were examined by comparing NARR estimates to ground-based meteorological observations of soil temperature, air temperature and shortwave radiation. Results indicated relatively good agreement between measured and estimated soil/air temperatures ($R^2 \approx 0.9$) and shortwave radiation ($R^2 \approx 0.8$) across year-round calibration and validation sites, relative to products such as NLDAS and GLDAS.

NARR estimates of downward shortwave radiation, T_{air} at 2 m and soil temperature at 0–10 cm (T_{soil}) were therefore incorporated into PolarVPRM. In the error analysis (Sect. 3.2), biases in NARR inputs were assessed, along with their contributions to errors in NEE. Similarly, in the validation at high-latitude Canadian sites (Sect. 3.1), model errors were examined in relation to biases in NARR estimates, which are much more substantial at these high-latitude, remote Canadian sites than in Alaska. Overall, NARR shortwave radiation, air

temperature and soil temperature, as well as MODIS EVI, LSWI and fractional snow cover area, are presently the best available inputs for high-latitude sites.

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Table 1. PolarVPRM vegetation classes, created by combining and aggregating CAVM and SYNMAP vegetation classes. SYNMAP tree classes are described according to leaf type (broad, needle or mixed) followed by leaf longevity (evergreen, deciduous, or mixed), as in Jung et al. (2006).

Veg class	Source	Description
Evergreen forest	SYNMAP	Trees needle evergreen; trees broad evergreen; trees mixed evergreen
Deciduous forest	SYNMAP	Trees needle deciduous; trees needle mixed; trees broad deciduous; Trees broad mixed; trees mixed deciduous; trees mixed mixed
Mixed tree/grass/ shrub forest	SYNMAP	Trees and shrubs; trees and grasses; trees and crops; crops
Shrubland	SYNMAP	Shrubs; shrubs and crops
Shrub tundra	SYNMAP	Shrubs and barren
Shrub tundra	CAVM	Prostrate dwarf-shrub, herb tundra; erect dwarf-shrub tundra; Low-shrub tundra
Graminoid tundra	SYNMAP	Grasses; grasses and crops
Graminoid tundra	CAVM	Rush/grass, forb, cryptogam tundra; graminoid, prostrate dwarf-shrub, forb tundra; Prostrate/hemiprostrate dwarf-shrub tundra; nontussock sedge, dwarf-shrub, moss tundra; tussock-sedge, dwarf-shrub, moss tundra
Barren/wetland	SYNMAP	Grasses and barren; barren
Barren/wetland	CAVM	Cryptogam, herb barren; cryptogam barren complex (bedrock); Sedge/grass, moss wetland; sedge, moss, dwarf-shrub wetland; Sedge, moss, low-shrub wetland; noncarbonate mountain complex; Carbonate mountain complex

Table 2. Summary of meteorological and land surface remote sensing inputs to PolarVPRM.

Input	Source	Spatial resolution	Temporal resolution
Shortwave radiation (W m^{-2})	NARR	0.3°	Three-hourly
Air temperature ($^\circ$ Kelvin)	NARR	0.3°	Three-hourly
Soil temperature ($^\circ$ Kelvin)	NARR	0.3°	Three-hourly
Fractional snow cover (%)	MODIS MOD10A2	500 m	Eight-day
Enhanced vegetation index (0–1)	MODIS MOD13A1	500 m	Sixteen-day
Land surface water index (0–1)	MODIS MOD09A1	500 m	Eight-day

Table 3. Calibration and validation sites for each vegetation type, and their locations.

Vegetation type	Calibration site	Validation sites	Latitude (°)	Longitude (°)
Shrub tundra	Daring Lake (DL)		64.869	−111.575
Shrub tundra		Cape Bounty (cb)	74.915	−109.574
Shrub tundra		Lake Hazen (lh)	81.823	−71.381
Shrub tundra		Iqaluit (iq)	63.7903	−68.560
Graminoid tundra	Ivotuk (IV)		68.487	−155.748
Graminoid tundra		Imnavait (Im) tussock tundra	68.606	−149.304
Graminoid tundra		Pond Inlet (pi)	72.693	−77.958
Wetland/barren	Atqasuk (AT)		70.470	−157.409
Wetland/barren		Barrow (Ba)	71.323	−156.626

Table 4. MBE and RMSE (in $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) from comparisons of three-hourly PolarVPRM NEE, to July 2008 eddy covariance observations of NEE at four Canadian Arctic validation sites.

	Cape Bounty (cb)	Iqaluit (iq)	Lake Hazen (lh)	Pond Inlet (pi)	Mean
Root mean squared error (RMSE)	0.66	1.01	0.57	0.92	0.79
Mean bias error (MBE)	0.33	−0.15	−0.39	0.44	0.06

Table 5. Error statistics (RMSE and MBE; in $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) found through the comparison of monthly mean, daily, and 3-hourly averaged estimates of NEE from PolarVPRM, CarbonTracker and FLUXNET Model-Tree Ensemble relative to observations of three-hourly, daily and monthly averages of NEE from Atqasuk (AT), Barrow (Ba), Daring Lake (DL), Imnavait (Im) and Ivotuk (IV) at a matching temporal resolution.

Resolution	Error	Model	AT	Ba	DL	Im	IV	Mean
Monthly	RMSE	PolarVPRM	0.42	0.93	0.42	1.61	0.59	0.79
Monthly	RMSE	CarbonTracker	0.57	0.48	0.92	1.58	0.86	0.88
Monthly	RMSE	FLUXNET MTE	1.10	1.13	1.40	2.14	1.19	1.39
Daily	RMSE	PolarVPRM	0.75	9.42	3.80	12.02	0.33	5.26
Daily	RMSE	CarbonTracker	2.87	4.74	6.21	10.83	2.90	5.51
3-hrly	RMSE	PolarVPRM	1.29	1.52	0.75	3.27	1.97	1.76
3-hrly	RMSE	CarbonTracker	1.61	1.20	2.20	4.45	2.91	2.47
Monthly	MBE	PolarVPRM	-0.14	-0.51	0.14	-1.15	0.02	-0.33
Monthly	MBE	CarbonTracker	0.03	-0.20	-0.37	-1.01	0.20	-0.27
Monthly	MBE	FLUXNET MTE	-0.64	-0.82	-1.03	-1.55	-0.43	-0.89
Daily	MBE	PolarVPRM	0.06	0.84	-0.38	1.37	-0.03	0.37
Daily	MBE	CarbonTracker	-0.22	0.42	-0.63	1.23	-0.23	0.12
3-hrly	MBE	PolarVPRM	-0.03	-0.65	0.23	-1.43	0.12	-0.35
3-hrly	MBE	CarbonTracker	0.26	-0.33	0.30	-1.27	0.42	-0.12

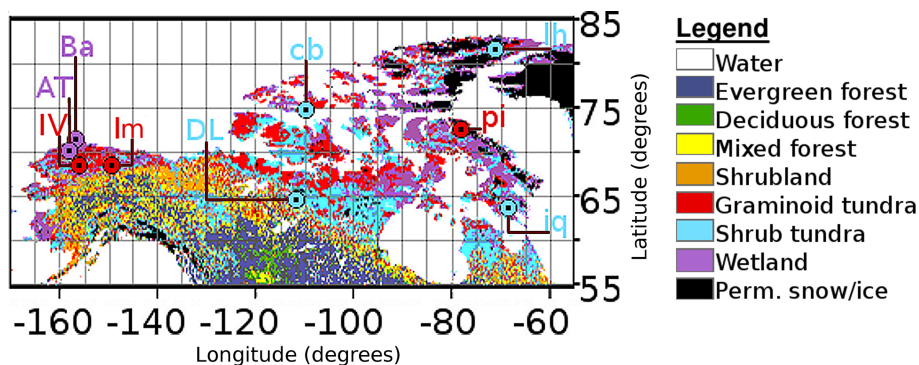


Figure 1. Map of all North American calibration and validation sites and their predominant vegetation types: graminoid tundra (red), shrub tundra (cyan) or wetland (purple). Calibration sites are indicated in all caps (e.g. AT), year-round validation sites are capitalized (e.g. Im), and growing season validation sites appear in lowercase (e.g. cb). For a summary of all study site locations, please refer to Table 3.

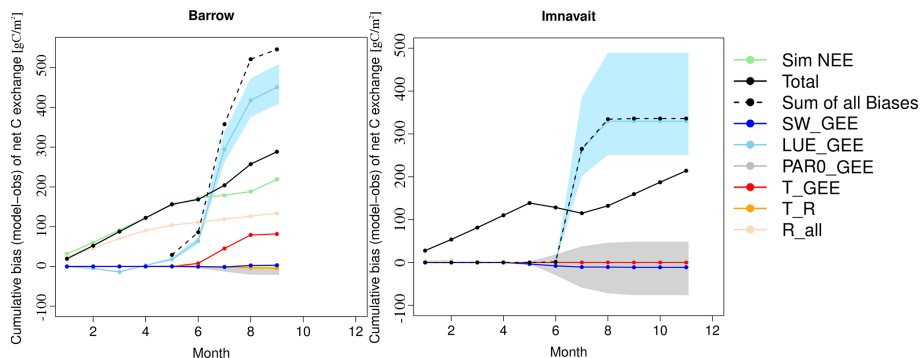


Figure 2. Cumulative monthly bias in PolarVPRM estimates of net C exchange at Barrow (left) and Imnavait (right), relative to eddy covariance observations at these sites. Errors in GEE are designated as being due to the associations between GEE and downward shortwave radiation (SW_GEE), GEE and light use efficiency (LUE_GEE), and of the parameter describing the association between GEE and PAR0 (PAR0_GEE). Shaded areas surrounding (PAR0_GEE) and (LUE_GEE) represent the range of biases possible from the determination of PAR0 and λ from eddy covariance observations. Total biases in temperature and GEE (T_GEE), and between temperature and respiration (T_R) are also described, along with the total biases in respiration (R_all) and NEE. Comparisons are shown for the range of months for which eddy covariance observations were acquired at Barrow in 2001 (January–September), and at Imnavait in 2008 (February–October).

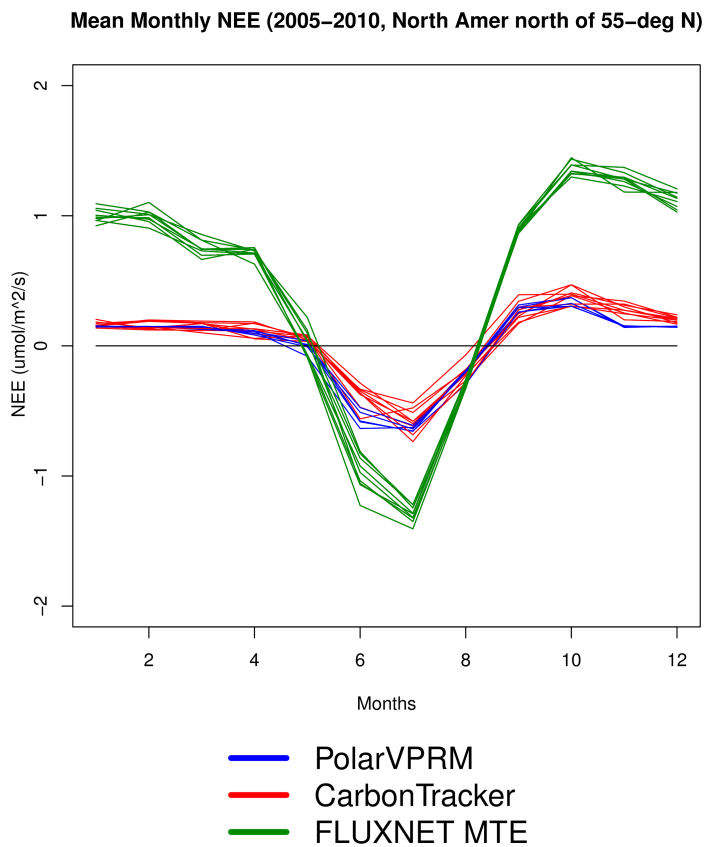


Figure 3. Monthly average NEE for high-latitude North America (north of 55° N from PolarVPRM (blue), FLUXNET MTE (green) and CarbonTracker (red). Average values are indicated for each year (2001–2009) individually.

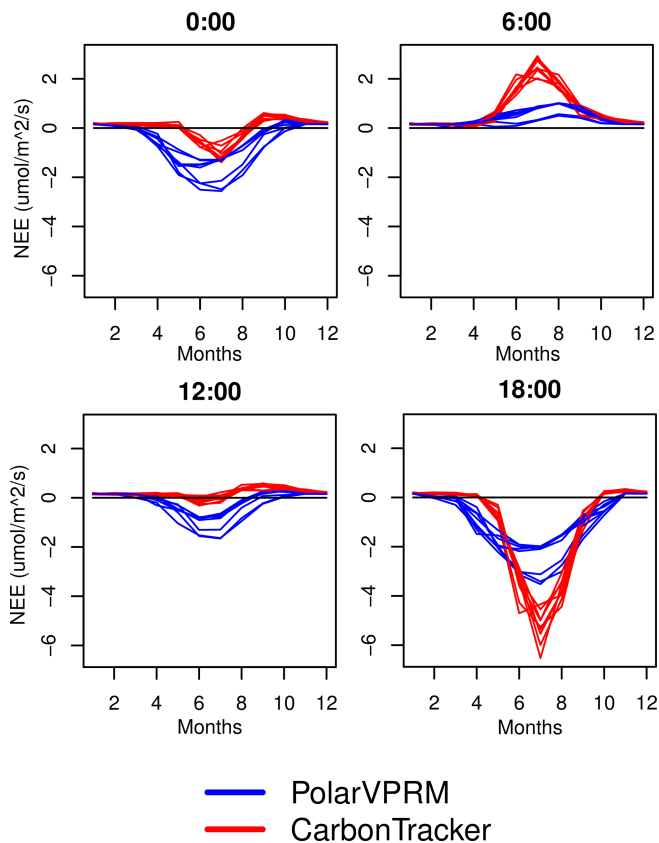


Figure 4. Spatially averaged North American high-latitude NEE from PolarVPRM (blue) and CarbonTracker (red). All estimates are averaged monthly at four distinct times of day, shown in Universal Time (UST) rather than according to local time zones.

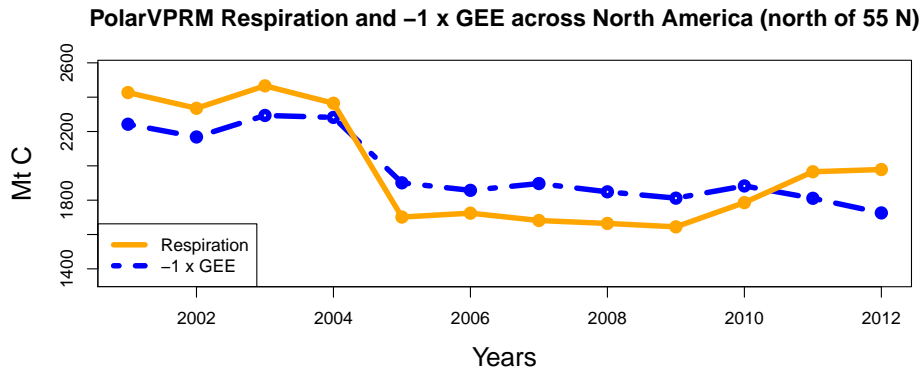


Figure 5. Estimated Relative contributions of PolarVPRM respiration and photosynthesis (GEE, plotted here as $-1 \times$ GEE) to inter-annual variability in the net carbon-C balance of the North American terrestrial region north of 55° N according to PolarVPRM (2001–2012) as indicated in black. For illustrative purposes, the line between carbon source (positive) and sink (negative NAHL) is indicated in orange.

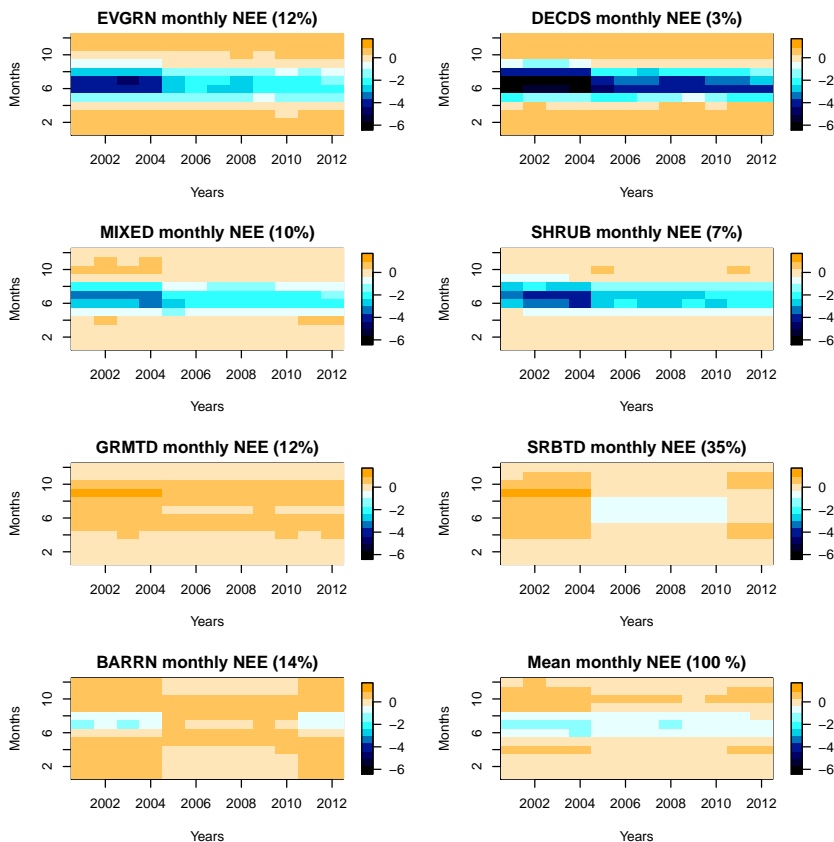


Figure 6. Average monthly NEE (in $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) for the entire North American region north of 55° N (Mean), as well as for seven vegetation classes within this region: deciduous forest (DECDS), evergreen forest (EVGRN), mixed forest (MIXED), shrub (SHRUB), graminoid tundra (GRMTD), shrub tundra (SRBTD), and barren/wetland (BARRN). The percentage of the model domain covered by each vegetation class is indicated in the title of each subplot.

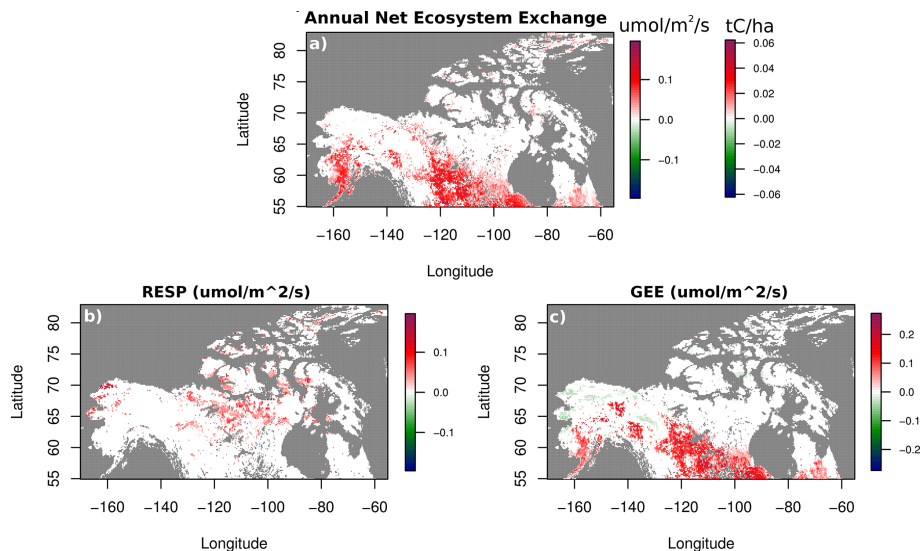


Figure 7. Sen's slope values, indicating the median change (2001–2012) in PolarVPRM estimates of mean annual NEE (a), respiration (b) and GEE (c). In (a), changes over time in NEE are indicated in both $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ and tC ha^{-1} using the same colour scheme. All Sen's slope values shown correspond to p values < 0.05 . Pixels with $>50\%$ fractional water content are indicated in grey. Please note that the negative sign convention in GEE has been maintained, meaning that a positive trend in GEE corresponds to diminished uptake of carbon through photosynthesis.

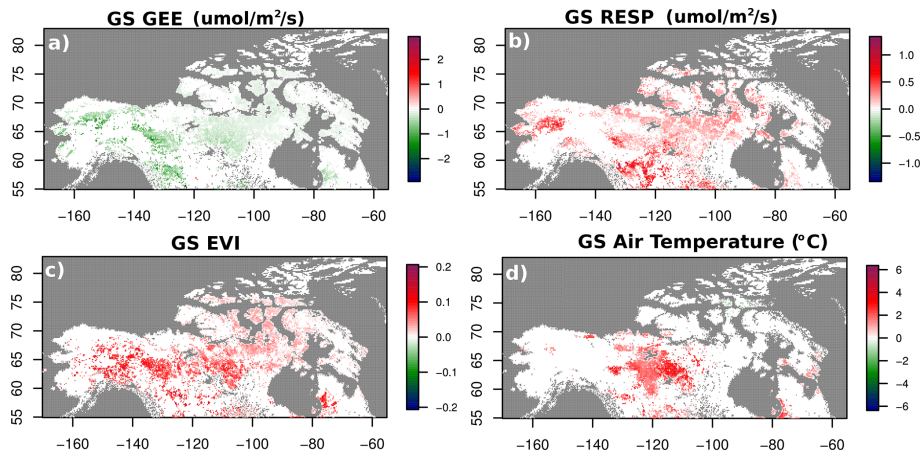


Figure 8. Sen's slope of median change (2001–2012) in PolarVPRM estimates of growing season carbon cycle variables, and driver data. All statistically significant (p value < 0.05) changes over time in carbon cycle variables and driver data are shown for the growing season (GS, when SCA $< 50\%$ AND GEE < 0). Please note that as the growing season includes only the period of time for which vegetation is productive at any pixel (GEE < 0), periods of time for which air temperature extremes or drought hinder photosynthesis are not included. The influences of rising EVI and air temperatures on increasing Arctic rates of photosynthesis are therefore made clear, whereas plots of annual GEE (Fig. 7) emphasize reductions in photosynthetic uptake of C by forest vegetation.

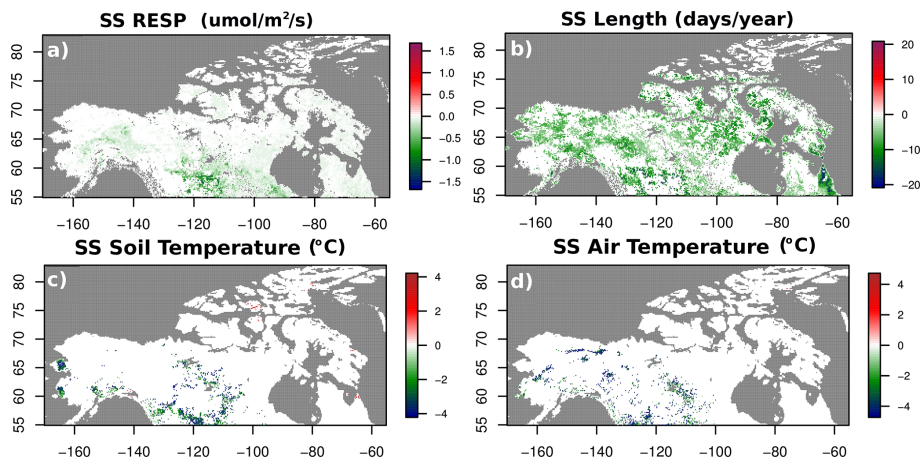


Figure 9. Sen's slope of median change (2001–2012) in PolarVPRM estimates of snow season (SS, when SCA \geq 50 %) carbon cycle variables, and driver data. Values are only shown for locations with a statistically significant change over time (p value < 0.05).