



**Polar Vegetation
Photosynthesis and
Respiration Model
(PolarVPRM)**

K. A. Luus and J. C. Lin

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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. 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 observations from nine North American sites, of which three were used in model calibration. PolarVPRM performed well over all sites. Model intercomparisons indicated that PolarVPRM showed slightly better agreement with eddy covariance observations relative to existing models. 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 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 the atmosphere. Positive feedbacks between the Arctic carbon cycle and the climate system 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

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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).

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, ≥ 1 km²). 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; Lin et al., 2011). 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 CO₂ efflux to the atmosphere (*R*) is positive.

$$NEE = GEE + R \quad (1)$$

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VPRM has 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 estimates of NEE across high-latitude regions.

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 $PAR = 1.98 \times SW$; 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 ($FAPAR_{PAV}$), 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). 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).

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

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

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

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

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

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(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. $0.06\text{ W}(\text{m}^{\circ}\text{C})^{-1}$ 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 Resolution Imaging Spectroradiometer (MODIS) observations of fractional snow cover area (SCA) (Appendix A). Snow season ($\text{SCA} \geq 50\%$) respiration is then calculated as a linear function of soil temperature, and growing season respiration ($\text{SCA} < 50\%$) is calculated as a piecewise linear function of air temperature:

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

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).

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 km × 1 km resolution. PolarVPRM estimates can likewise be generate at all resolution $\geq 1 \text{ km}^2$.

The North American high-latitude spatial resolution selected for this project is $1/6^\circ \times 1/4^\circ$ (latitude × longitude), and so vegetation classes is regrided 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 (Luus et al., 2013b) (soil moisture, air temperature, and vegetation opacity). This classification is therefore likely to capture the varying responses of the high-latitude (HL) carbon cycle to meteorological and environmental conditions.

Each vegetation class contains six parameters which are set according to meteorological and eddy covariance (EC) tower observations from calibration sites:

- PAR_0 , which represents the sensitivity of photosynthetic uptake to the quantity of incoming shortwave radiation

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- λ , which represents light use efficiency of vegetation, and also acts as a scaling parameter
- α and β , regression coefficients describing the linear association between air temperature and growing season respiration ($R = \alpha T_{\text{air}} + \beta$)
- α_s and β_s , regression coefficients describing 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 regrided to the PolarVPRM spatial domain (NAHL, $1/6^\circ \times 1/4^\circ$ latitude \times longitude) using bilinear interpolation in R. PolarVPRM was run at NARR's native temporal resolution (three-hourly), although it could easily be run at a much finer resolution with higher resolution meteorological inputs. MODIS was linearly interpolated to three-hourly timesteps. For a complete discussion of the changes made to the MODIS inputs, and of the reason why these 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

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mainly of wet sedges, moss, lichens and grasses (Oechel et al., 1995; Harazono et al., 2003). The Atqasuk EC site is located ≈ 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 Ivtok (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). Ivtok is a moist acidic tussock tundra site located ≈ 200 km south of Atqasuk (Thompson et al., 2006; Laskowski, 2010), and Imnavait is located ≈ 200 km east of Ivtok. 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 Ivtok (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 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 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, Ivtok 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), Ivtok (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

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of another model and therefore does not represent a direct measurement of CO₂ flux (Barr et al., 2004).

Respiration parameters were set using simple linear regression of air temperature and nighttime NEE (α and β), or subnivean soil temperature and 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. PAR₀ 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 GEE. 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 at a spatial resolution of 1/6° × 1/4° (latitude × 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–).

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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:

$$5 \quad \text{MBE} = n^{-1} \sum_{i=1}^n \text{pred}_i - \text{obs}_i \quad (7)$$

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

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 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.

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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 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. Biases occurring due to mis-parametrization are assessed by refitting all parameters at 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. 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 by existing models with different formulations, and all models were compared against EC NEE, which was upsampled from a half-hourly temporal resolution to three-hourly and

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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 averaged for the entire terrestrial region north of 55° N at a monthly resolution for each year (2001–2012). Visual examination of these plots provided insights into differences in inter-annual variability, and in estimates of the total carbon cycle by all three models. Further analysis then consisted of creating similar plots examining PolarVPRM and CarbonTracker model output at distinct time slices, 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. 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. 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 ≥ 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)

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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 (model-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 ($< 0.01 \text{ t C ha}^{-1}$) cumulative biases in net C exchange at these validation sites.

At Barrow and Imnavait, 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 vegetation at the calibration sites (AT and IV) showed a diminished photosynthetic response to light 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 λ were calculated for Barrow and Imnavait, values of 0.29 and 0.34 were identified.

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3.3 Model inter-comparison

Comparisons of mean monthly NEE by PolarVPRM, Carbon-Tracker 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 than CarbonTracker (Table 5). PolarVPRM appears to have lower error terms than CarbonTracker mainly 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.

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man 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.

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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

- 5 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

10 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 ($> 283\text{ K}$) (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).

25 In order to use MOD10A2 observations effectively, some filtering and smoothing techniques were applied to the remote-sensing observations before they were included

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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

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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.

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

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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 (° Kelvin)	NARR	0.3°	Three-hourly
Shortwave radiation (° 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

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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

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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

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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 and 3-hourly estimates of NEE from PolarVPRM, CarbonTracker and FLUXNET Model-Tree Ensemble relative to observations of three-hourly and monthly 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
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
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

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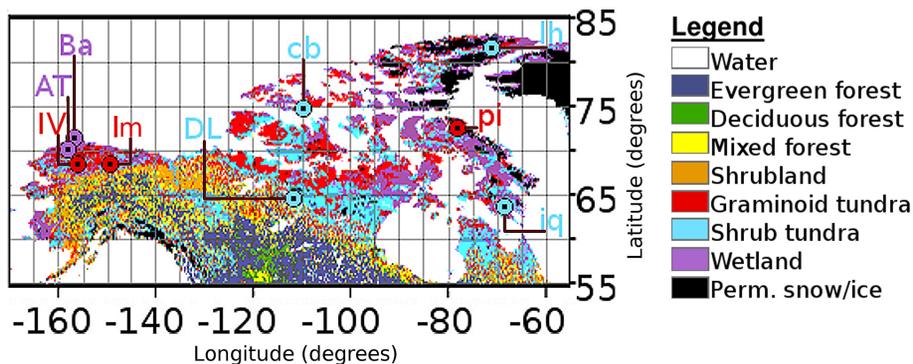


Figure 1. Map of all North American calibration and validation sites and their predominant vegetation types: graminoid tundra (red), shrub tundra (cyan) or wetland (purple). Calibration sites are indicated in all caps (e.g. AT), year-round validation sites are capitalized (e.g. Im), and growing season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

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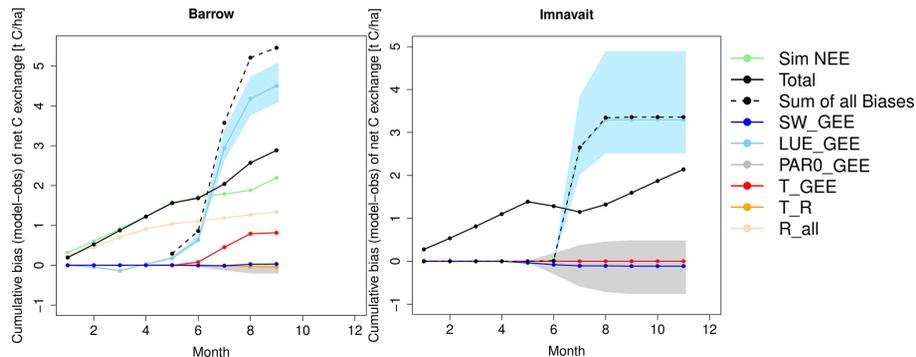


Figure 2. Cumulative monthly bias in PolarVPRM estimates of net C exchange at Barrow (left) and Imnavait (right), relative to eddy covariance observations at these sites. Errors in GEE are designated as being due to the associations between GEE and downward shortwave radiation (SW_GEE), GEE and light 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).

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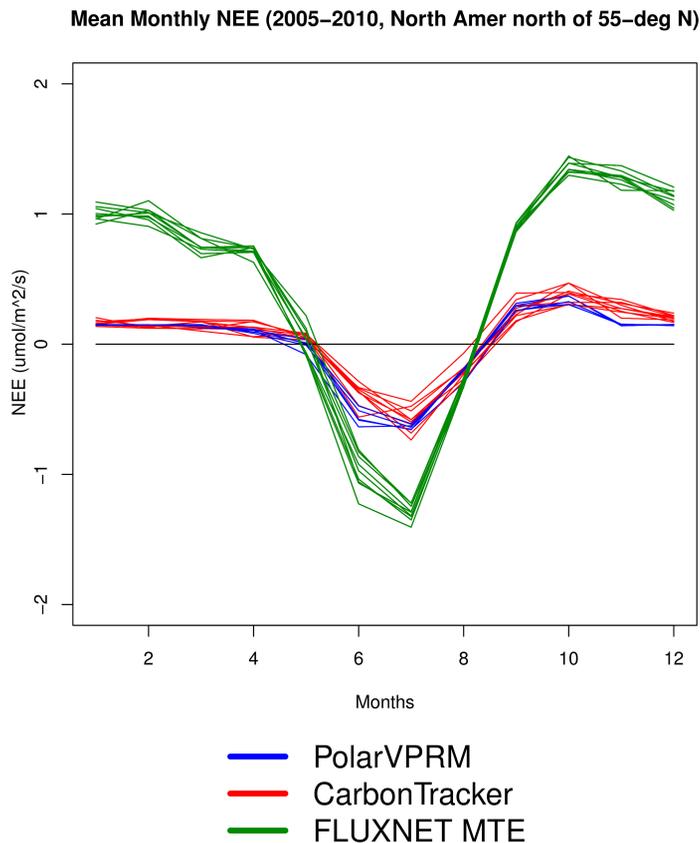


Figure 3. Monthly average NEE for high-latitude North America (north of 55° N from PolarVPRM (blue), FLUXNET MTE (green) and CarbonTracker (red)). Average values are indicated for each year (2001–2009) individually.

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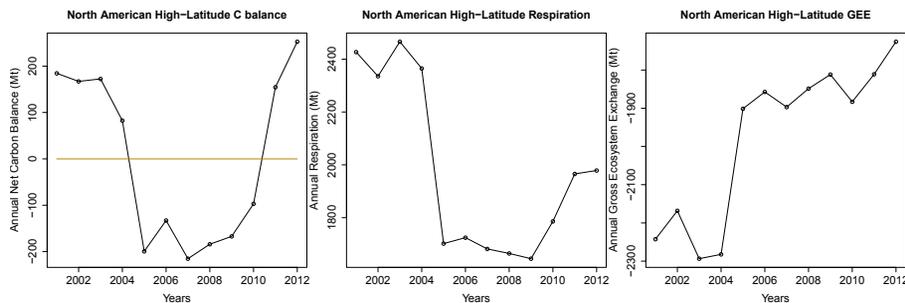


Figure 5. Estimated net carbon balance of the North American region north of 55° N according to PolarVPRM (2001–2012) as indicated in black. For illustrative purposes, the line between carbon source (positive) and sink (negative) is indicated in orange.

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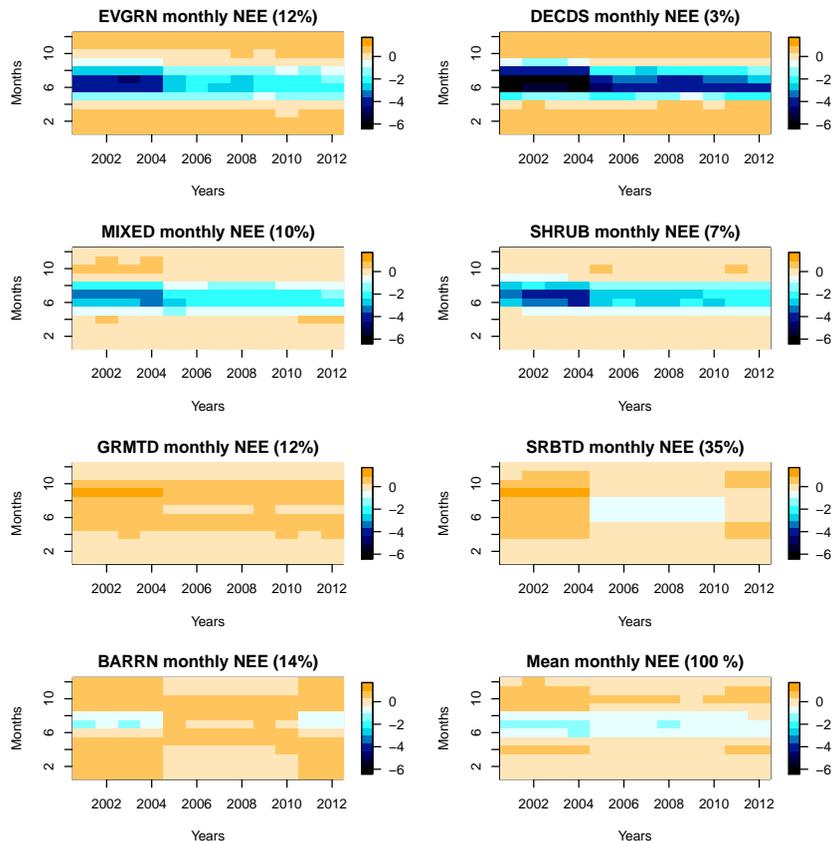


Figure 6. Average monthly NEE (in $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) for the entire North American region north of 55°N (Mean), as well as for seven vegetation classes within this region: deciduous forest (DECDS), evergreen forest (EVGRN), mixed forest (MIXED), shrub (SHRUB), graminoid 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.

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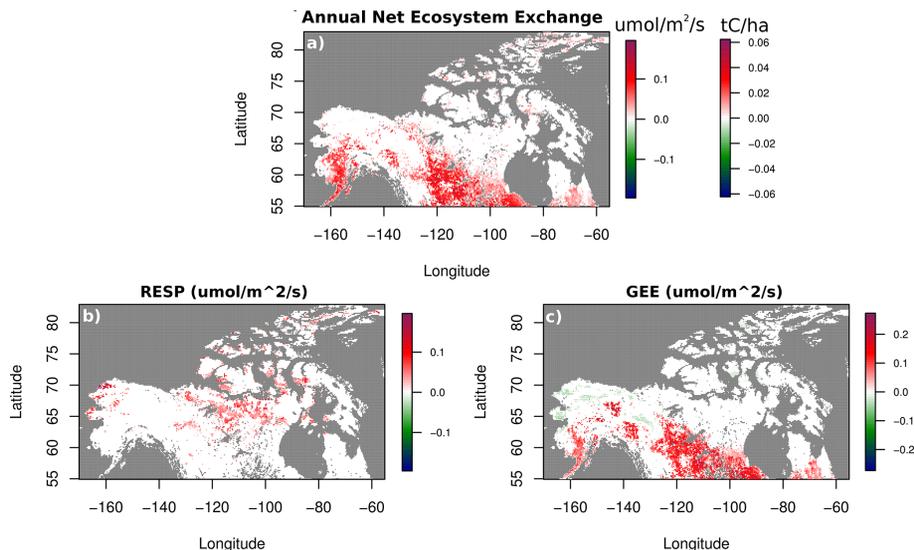


Figure 7. Sen's slope values, indicating the median change (2001–2012) in PolarVPRM estimates of mean annual NEE **(a)**, respiration **(b)** and GEE **(c)**. In **(a)**, changes over time in NEE are indicated in both $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ and tC ha^{-1} using the same colour scheme. All Sen's slope values shown correspond to p values < 0.05 . 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.

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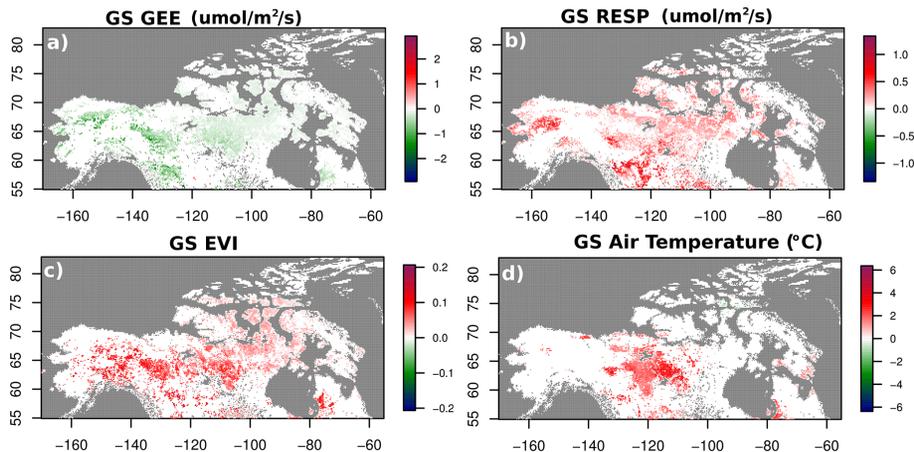


Figure 8. Sen's slope of median change (2001–2012) in PolarVPRM estimates of growing season carbon cycle variables, and driver data. All statistically significant (p value < 0.05) changes over time in carbon cycle variables and driver data are shown for the growing season (GS, when $SCA < 50\%$ AND $GEE < 0$). 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.

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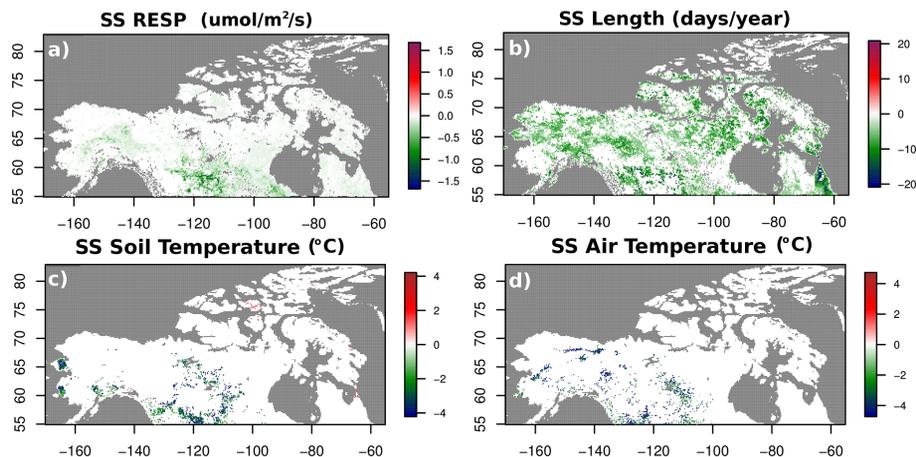


Figure 9. Sen's slope of median change (2001–2012) in PolarVPRM estimates of snow season (SS, when SCA \geq 50%) carbon cycle variables, and driver data. Values are only shown for locations with a statistically significant change over time (p value $<$ 0.05).

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