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# Tundra photosynthesis captured by satellite-observed solar-induced chlorophyll fluorescence

K. A. Luus<sup>1</sup>, R. Commane<sup>2</sup>, N. C. Parazoo<sup>3</sup>, J. S. Benmergui<sup>2</sup>,  
S. E. Euskirchen<sup>4</sup>, C. Frankenberg<sup>5</sup>, J. Joiner<sup>6</sup>, J. Lindaas<sup>2,7</sup>, C. E. Miller<sup>3</sup>,  
W. C. Oechel<sup>8,9</sup>, D. Zona<sup>8,10</sup>, S. Wofsy<sup>2</sup>, and J. C. Lin<sup>11</sup>

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Corresponding author: K.A. Luus, (kristina.luus@gmail.com)

<sup>1</sup>Centre for Applied Data Analytics  
Research, Dublin, Ireland

<sup>2</sup>Harvard School of Engineering and  
Applied Sciences, Cambridge MA 02138,  
USA

<sup>3</sup>NASA Jet Propulsion Lab, 4800 Oak  
Grove Drive, Pasadena, CA 91109, USA

<sup>4</sup>Institute of Arctic Biology, University of  
Alaska Fairbanks, 902 N. Koyukuk Dr. P.O.  
Box 757000, Fairbanks, AK 99775, USA

<sup>5</sup>Environmental Science & Engineering,  
California Institute of Technology, CA  
91125, USA

**Key Points.**

- Alaskan tundra has a shorter growing season and less net carbon uptake than typically estimated using satellite-derived vegetation indices.
- Comparisons against site and aircraft observations of CO<sub>2</sub> indicate that solar-induced fluorescence (SIF) captures tundra photosynthesis.
- SIF-driven modeling of tundra photosynthesis enables improved model accuracy, and enhanced understanding of the carbon-climate system.

**Abstract.** Accurately quantifying the timing and magnitude of respiration and photosynthesis by high-latitude ecosystems is important for under-

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<sup>6</sup>NASA Goddard Space Flight Center,  
Greenbelt, MD 20771, USA

<sup>7</sup>Department of Atmospheric Science,  
Colorado State University, Fort Collins, CO,  
80523

<sup>8</sup>San Diego State University, San Diego,  
CA 92182, USA

<sup>9</sup>The Open University, Walton Hall,  
Milton Keynes MK7 6AA, UK

<sup>10</sup>University of Sheffield, Sheffield, South  
Yorkshire S10 2TN, UK

<sup>11</sup>University of Utah, Salt Lake City, UT  
84112, USA

standing how a warming climate influences global carbon cycling. Data-driven estimates of photosynthesis across Arctic regions often rely on satellite-derived enhanced vegetation index (EVI); we find that satellite observations of solar-induced chlorophyll fluorescence (SIF) provide a more direct proxy for photosynthesis. We model Alaskan tundra CO<sub>2</sub> cycling (2012–2014) according to temperature and shortwave radiation, and alternately input EVI or SIF to prescribe the annual seasonal cycle of photosynthesis. We find that EVI-based seasonality indicates spring “green-up” to occur nine days prior to SIF-based estimates, and that SIF-based estimates agree with aircraft and tower measurements of CO<sub>2</sub>. Adopting SIF, instead of EVI, for modeling the seasonal cycle of tundra photosynthesis can result in more accurate estimates of growing season duration and net carbon uptake by arctic vegetation.

## 1. Introduction

1 Land-atmosphere CO<sub>2</sub> exchange can only be continuously measured at small scales (<1  
2 km<sup>2</sup>), and CO<sub>2</sub> concentrations measured by towers and aircraft are spatially and tempo-  
3 rally limited. Accurate, fine-resolution model estimates of net ecosystem CO<sub>2</sub> exchange  
4 (NEE) across large regions are therefore needed in order to gain insight into how carbon  
5 cycling by high-latitude ecosystems influences atmospheric concentrations of CO<sub>2</sub> and the  
6 global climate system.

7 Vegetation influences on rates of photosynthesis (e.g. phenology, biomass, leaf area,  
8 etc.) are typically inferred at regional scales using indices derived from satellite-observed  
9 visible and infrared reflectance, such as the normalized difference vegetation index (NDVI)  
10 and enhanced vegetation index (EVI) [Barichivich *et al.*, 2013; Wang *et al.*, 2015]. These  
11 indices are calculated as normalized ratios of visible and infrared reflectance, and rely  
12 on the tendency for vegetation chlorophyll to absorb visible (0.4–0.7 μm) radiation, and  
13 mesophyll to reflect near-infrared (0.7–1.1 μm) radiation. Larger EVI and NDVI values  
14 are indicative of denser or greener leaf cover [Wang *et al.*, 2002; Sims *et al.*, 2006], which  
15 can be interpreted as greater photosynthetic capacity.

16 Passive solar-induced chlorophyll fluorescence (SIF) provides a more direct proxy for  
17 photosynthesis [Yang *et al.*, 2015] independent of ancillary information or modeling steps,  
18 and can be acquired from ground- and satellite-based observations [Frankenberg *et al.*,  
19 2014]. SIF occurs as a direct result of light absorption by the chlorophyll complex during  
20 photosynthesis [Porcar-Castell *et al.*, 2014].

21 Photosynthesis is therefore directly correlated with SIF [*Frankenberg et al.*, 2011a],  
22 whereas EVI is associated with the capacity of the land surface for photosynthesis. EVI  
23 is more susceptible to being confounded with non-vegetated land surface properties than  
24 SIF. Unlike SIF, EVI has been observed to remain elevated ( $>0$ ) throughout most of  
25 the arctic snow season [Figure S2], and to increase during the time period over which  
26 vegetation is revealed through snowmelt. Conversely, SIF remains near zero throughout  
27 the non-growing season, and increases in response to photosynthesis [Figure 1]. Through  
28 comparisons against aircraft and tower measurements of  $\text{CO}_2$ , we show here that more  
29 realistic model estimates of tundra photosynthesis can be generated when the seasonal  
30 cycle is prescribed using SIF rather than EVI.

### 1.1. Overview

31 We present satellite-data-driven estimates of Alaskan tundra NEE (three-hourly,  
32  $0.17^\circ \times 0.25^\circ$ , 2012–2014) using PolarVPRM [*Luus and Lin*, 2015], a low dimensional,  
33 spatially and temporally resolved model developed according to empirical associations  
34 between site-scale meteorology and NEE. PolarVPRM-EVI has previously been applied  
35 to estimate Alaskan [*Karion et al.*, 2016] and northern Canadian [*Luus and Lin*, 2015]  
36 NEE.

37 We generate model estimates of Alaskan NEE, and allow the seasonal cycle of pho-  
38 tosynthesis to alternately be driven by EVI or SIF. We then confront EVI-driven and  
39 SIF-driven estimates of Alaskan NEE (2012–2014) across tundra-dominated ( $>80\%$  tun-  
40 dra) regions with measurements of NEE from established eddy covariance sites [Table 1;  
41 Figures 2 & S1], and observations of regional-scale  $\text{CO}_2$  fluxes optimized from NASA's

42 CARVE (Carbon in the Arctic Reservoirs Vulnerability Experiment) airborne CO<sub>2</sub> obser-  
43 vations [Miller and Dinardo, 2012].

44 We find that PolarVPRM-SIF is better able to capture the timing and duration of the  
45 tundra growing season (time period over which mean weekly NEE<0) than PolarVPRM-  
46 EVI. PolarVPRM-EVI overestimates growing season length, despite the application of  
47 strategies to reduce spring and fall EVI, and the inclusion of scaling factors to re-  
48 duce PolarVPRM-EVI photosynthesis at the start and end of the growing season (when  
49 EVI<50% annual EVI). PolarVPRM-SIF provides improved accuracy in regional esti-  
50 mates of the Alaskan carbon balance [Figure S5].

## 2. Methods

51 Methods applied to: 1) observe site-scale CO<sub>2</sub> fluxes; 2) estimate duration of photosyn-  
52 thesis regionally from EVI and SIF; 3) generate regional model estimates of net ecosystem  
53 CO<sub>2</sub> exchange; and 4) calculate regional CO<sub>2</sub> fluxes from CARVE CO<sub>2</sub> observations, are  
54 described below.

### 2.1. Site-scale CO<sub>2</sub> observations

55 Measurements of net ecosystem CO<sub>2</sub> exchange (NEE) were obtained from established  
56 Alaskan sites using eddy covariance towers, which were used for model calibration and  
57 validation. These sites include a sparsely forested thermokarst bog in central Alaska  
58 (Bonanza Creek) [Euskirchen *et al.*, 2014], two wet sedge sites (Atqasuk & Barrow) [Kwon  
59 *et al.*, 2006; Lipson *et al.*, 2012], and a site containing wet sedge and tussock tundra  
60 (Imnavait) [Euskirchen *et al.*, 2012] [Table 1].

### 2.2. EVI and SIF

61 Moderate Resolution Imaging Spectroradiometer (MODIS) EVI observations [*Huete*  
62 *et al.*, 1999] were acquired from portions of the 16-day MOD13A1 dataset with good  
63 QC flags, and were smoothed using a loess filter, with spatial and temporal interpolation  
64 applied to remove missing values, and linear interpolation to ensure three-hourly estimates  
65 for all pixels. Since MODIS EVI is reported according to the maximum value observed  
66 during a given time period, it was assumed that these maximum values would correspond  
67 to the final day of observations during green-up, and to the first day of observations  
68 following the attainment of maximum annual EVI at each pixel. This approach was  
69 selected specifically to reduce EVI values in spring and autumn.

70 SIF was acquired across high-latitude regions using the Orbiting Carbon Observatory-2  
71 (OCO-2) [*Frankenberg et al.*, 2011b] and Global Ozone Monitoring Experiment2 (GOME-  
72 2) [*Joiner et al.*, 2013] instruments. Retrievals from GOME-2 on MetOp-A use channel 4,  
73 with 734–758 nm wavelengths and an  $\approx 0.5$  nm spectral resolution were collected at a 1-2  
74 day revisit time, and developed into a  $0.5 \times 0.5$  degree, monthly, bias-corrected product  
75 (GOME2\_F V26) by *Joiner et al.* [2013, In Press].

76 Retrievals from OCO-2 were taken from the Version 7 product using an algorithm  
77 described in *Frankenberg et al.* [2011b]. We used the average of Nadir soundings at 757  
78 nm and 771 nm bands with overpass of 2:15 pm Local Time, revisit time of a few weeks,  
79 and footprint of  $1.3 \times 2.25$  km<sup>2</sup>, where the 771 nm band was multiplied by 1.35 due to its  
80 smaller signal. Soundings were aggregated to monthly averages on a  $0.17^\circ \times 0.25^\circ$  grid using  
81 a minimum of 5 soundings per bin. A full-year of OCO-2 SIF estimates was generated by  
82 combining SIF observations from 2014 (Sep–Dec) and 2015 (Jan–Aug). Monthly averages



of OCO-2 SIF were generated using all available data from September 2014–August 2015, and these monthly values were repeated for all years (2012–2014).

We included GOME-2 SIF and OCO-2 SIF at a monthly resolution because our preliminary findings indicated monthly SIF values to be reliable and adequate, in agreement with *Joiner et al.* [2014]. At the regional scale, median GOME-2 SIF and OCO-2 SIF values were separately calculated for each month, and each vegetation class [Figure S4].

SIF values for each PolarVPRM pixel ( $0.17^\circ \times 0.25^\circ$ ) were then calculated as the weighted mean of SIF according to component vegetation fractions, and three-hourly estimates of SIF were generated through linear interpolation of monthly values.

### 2.3. Estimating NEE

Estimates of NEE were generated for Alaska at a three-hourly,  $0.17^\circ \times 0.25^\circ$  resolution using the Polar Vegetation Photosynthesis and Respiration Model (PolarVPRM) [*Luus and Lin*, 2015], a high-latitude version of VPRM [*Mahadevan et al.*, 2008]. PolarVPRM is a parametric fit to the classic hyperbolic form of the light response curve for an ecosystem of a defined vegetation type. Regional-scale estimates of NEE were acquired by calculating the weighted sum of gross ecosystem exchange ( $GEE = -1 \times GPP$ ) and ecosystem respiration ( $R$ ) at each pixel according to its fractional vegetation cover [*Walker et al.*, 2005; *Jung et al.*, 2006; *Luus et al.*, 2013a] (see Figure S4). For a full description, evaluation and error attribution of PolarVPRM, refer to *Luus et al.* [2013b]; *Luus and Lin* [2015].

#### 2.3.1. PolarVPRM inputs

Meteorological inputs such as soil temperature at 0–10 cm ( $T_{\text{soil}}$ ), air temperature at 2 m ( $T_{\text{air}}$ ), and downward shortwave radiation ( $PAR = 1.98 \cdot SW$ ) were provided by the

105 North American regional reanalysis (NARR) [Mesinger *et al.*, 2006]. Land surface con-  
 106 ditions were estimated from MODIS snow cover area (MOD10A2) [Hall *et al.*, 2002],  
 107 and land surface water index (LSWI) calculated from surface reflectance (MOD09A1)  
 108 [(MODAPS), 2016].

109 We prescribe the seasonal cycle of vegetation green-up and senescence alternately  
 110 by Moderate Resolution Imaging Spectroradiometer (MODIS) EVI [Huete *et al.*, 1999],  
 111 Global Ozone Monitoring Experiment2 (GOME-2) SIF [Joiner *et al.*, 2013], or Orbiting  
 112 Carbon Observatory-2 (OCO-2) SIF [Frankenberg *et al.*, 2014], where SIF is normalized  
 113 according to the cosine of solar zenith angle ( $\cos(\text{SZA})$ ) [Figure 1].

### 114 2.3.2. PolarVPRM equations

115 Ecosystem respiration was calculated as a function of air (growing season) and soil  
 116 (snow season) temperature depending on MODIS-derived snow cover area, using a formu-  
 117 lation that maximizes effective capture of subnivean and growing season drivers of arctic  
 118 respiration [Luus *et al.*, 2013c], including soil freeze-thaw cycles [Equation 3]. GEE was  
 119 calculated according to air temperature at 2 m ( $T_{\text{scale}}$ ) and photosynthetically active ra-  
 120 diation ( $\text{PAR}=1.98 \times \text{shortwave radiation}$ ), such that photosynthesis (GEE) is greatest  
 121 when conditions are warm and sunny. The seasonal cycle of GEE was driven alternately  
 122 by MODIS EVI [Equation 1] and SIF [Equation 2].

$$\text{GEE} = \lambda \cdot \text{EVI} \cdot T_{\text{scale}} \cdot P_{\text{scale}} \cdot \frac{1}{1 + \frac{\text{PAR}}{\text{PAR}_0}} \cdot \text{PAR} \quad (1)$$

$$\text{GEE} = \lambda \cdot T_{\text{scale}} \cdot \frac{\text{SIF}}{\cos(\text{SZA})} \cdot \frac{1}{1 + \frac{\text{PAR}}{\text{PAR}_0}} \cdot \text{PAR} \quad (2)$$

$$R = \begin{cases} \alpha_{\text{grow}} \cdot T_{\text{air}} + \beta_{\text{grow}} : \text{snow cover} < 50 \% \\ \alpha_{\text{snow}} \cdot T_{\text{soil}} + \beta_{\text{snow}} : \text{snow cover} \geq 50 \% \end{cases} . \quad (3)$$

### 123 2.3.3. PolarVPRM parameters

124 All parameters were calculated empirically so as to capture associations between site  
 125 meteorology and eddy covariance NEE. The model parameters  $\text{PAR}_0$  and  $\lambda$  [Table 2]  
 126 refer to the half-saturation value of PAR and light-use efficiency at low light levels, re-  
 127 spectively.  $\text{PAR}_0$  was first calculated from PAR and GPP using `nls` non-linear curve  
 128 fitting in R [*R Core Team*, 2013], and  $\lambda$  was then calculated as the slope of the linear  
 129 regression of observed and modeled three-hourly GEE (with  $\lambda=1$ , and intercept=0) at  
 130 three eddy covariance sites [Table 1]. Estimates across forested regions in interior Alaska  
 131 were generated using  $\text{PAR}_0$  and  $\lambda$  values in *Mahadevan et al.* [2008]. Linear regression was  
 132 used to determine the slope ( $\alpha$ ) and intercept ( $\beta$ ) of the associations between nighttime  
 133 NEE (respiration) and soil/air temperature, using only values for which PAR indicated  
 134 night and  $\text{NEE} > 0$ .

135 SIF-based models used identical  $\text{PAR}_0$  values as EVI-based models, since PAR was  
 136 unchanged. However, to account for the different magnitudes of OCO-2 SIF and GOME-  
 137 2 SIF relative to MODIS EVI,  $\lambda$  values were multiplied by a scaling factor describing the  
 138 slope of EVI-based vs. SIF-based GEE at calibration eddy covariance sites. In this way, it  
 139 was ensured that differences in EVI-based and SIF-based outputs would arise from inputs  
 140 alone. PolarVPRM-EVI NEE additionally benefits from having corrections implemented  
 141 so as to reduce the length of the modeled growing season: inclusion of scalars described  
 142 in Section 2.3.4 ( $P_{\text{scale}}$ ,  $T_{\text{scale}}$ ), and pre-processing of EVI as described in Section 2.2.

### 143 2.3.4. PolarVPRM scalars

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

144 The temperature scalar [Equation 4] is calculated according to minimum ( $T_{\text{min}}=0\text{°C}$ )  
 145 and maximum ( $T_{\text{max}}=40\text{°C}$ ) temperature thresholds for photosynthesis, as well as an op-  
 146 timal temperature ( $T_{\text{opt}}$ ).  $T_{\text{opt}}$  was set according to values in literature [*Tieszen*, 1973;  
 147 *Chapin III*, 1983; *O'Sullivan et al.*, 2016] rather than being optimized in order to avoid  
 148 parameter instability arising from correlations between temperature and light-use param-  
 149 eters [*Mahadevan et al.*, 2008] [Table 2].

150 In EVI-driven PolarVPRM,  $T_{\text{scale}}$  [Equation 4] ensures that GEE=0 during the snow sea-  
 151 son (when  $T_{\text{air}} < 0\text{°C}$ ), and reduces GPP at the start and end of the snow season, when air  
 152 temperatures approach freezing. In contrast, SIF GPP estimates showed little sensitivity  
 153 to  $T_{\text{scale}}$  and did not require any artificial suppression of non-growing-season photosyn-  
 154 thesis. Final estimates of GPP by both versions of PolarVPRM include  $T_{\text{scale}}$  so as to  
 155 capture mid-growing season reductions in photosynthesis due to heat stress [*O'Sullivan*  
 156 *et al.*, 2016] in both models, and to reduce cold-season and shoulder-season GPP overes-  
 157 timates by PolarVPRM-EVI.

$$P_{\text{scale}} = \frac{1 + \text{LSWI}}{2} \quad (5)$$

158 The phenology scalar,  $P_{\text{scale}}$ , is prescribed in the EVI version of VPRM and PolarVPRM  
 159 to reduce photosynthesis when EVI is at  $< 50\%$  of maximum annual pixel-specific EVI,  
 160 so as to reduce overestimates of photosynthesis in spring and fall [Equation 5]. This  
 161 was applied in the EVI version of PolarVPRM to reduce errors arising from elevated  
 162 ( $>0$ ) EVI before and after the growing season, but was not needed in the SIF version of

163 PolarVPRM. In short, the two scalar terms,  $T_{\text{scale}}$  and  $P_{\text{scale}}$ , both reduce overestimates  
164 of GPP by PolarVPRM-EVI, especially at the start and end of the growing season.

## 2.4. Regional-scale CO<sub>2</sub> observations

165 CO<sub>2</sub> concentrations were measured during Carbon in Arctic Reservoirs Vulnerability  
166 Experiment (CARVE) flight campaigns, which were conducted over Alaska throughout the  
167 2012-2014 growing seasons. The NASA C-23B (N430NA) aircraft was based in Fairbanks,  
168 Alaska, USA, and flights sampled the region between 55°–72°N and 165°–138°W. CO<sub>2</sub>,  
169 CH<sub>4</sub> and CO were measured using two independent cavity ringdown spectrometers: one  
170 operated wet (G1301-m in 2012 and G2401-m from 2013 onward) [Karion *et al.*, 2013]  
171 and one dry (G2401-m) [Chang *et al.*, 2014]. Each analyzer was calibrated throughout  
172 the flights, with gap-filling to ensure a continuous 5 s time series.

173 Airborne CO<sub>2</sub> concentrations (ppm) were modeled to gain insight into the magnitudes  
174 and locations of CO<sub>2</sub> fluxes ( $\mu\text{mol m}^{-2} \text{ s}^{-1}$ ) giving rise to observed CO<sub>2</sub> concentrations.  
175 First, modeled column CO<sub>2</sub> concentrations were calculated for altitude profiles within  
176 each flight using pWRF-STILT (polar variant of Weather Forecasting and Research -  
177 Stochastic Time Inverted Lagrangian Transport model) [Henderson *et al.*, 2015; Lin *et al.*,  
178 2003] mapping of land surface influences on mean three-hourly CO<sub>2</sub> concentrations. These  
179 results are provided on a  $0.5^\circ \times 0.5^\circ$  grid that represents the response of each receptor to a  
180 unit emission of CO<sub>2</sub> at each grid square (in  $\frac{\mu\text{mol}}{\text{mol}} / \frac{\mu\text{mol}}{\text{m}^2\text{s}}$ ). The column integral represents  
181 the mass loading of regional emissions on the atmosphere from the surface to the top of  
182 the mixed layer. The column enhancement of CO<sub>2</sub> mole fractions combines all fluxes to  
183 give an integrated signal used in the column analysis. Episodic or point sources of CO<sub>2</sub>  
184 will have little influence on this integrated signal.

185 Alaskan NEE was calculated from these CARVE CO<sub>2</sub> datasets. Mean monthly addi-  
186 tive fluxes ( $\delta F$ , in  $\frac{\mu\text{mol}}{\text{m}^2\text{s}}$ ) were calculated as the difference between the integrated column  
187 enhancement of the observed and modeled CO<sub>2</sub> for each profile, and were calculated  
188 separately using PolarVPRM-EVI and PolarVPRM-SIF. CARVE-constrained estimates  
189 of NEE were then generated by adding  $\delta F$  to the mean spatially averaged NEE from  
190 PolarVPRM-EVI and PolarVPRM-SIF.

191 CARVE NEE fluxes are a result of mass balance considerations based upon tracer  
192 variations in the atmospheric planetary boundary layer, which is the most direct means we  
193 have possible to observe and quantify regional carbon fluxes. The mean of the 273 CARVE  
194 column profiles used for this approach is shown in Figure 3, along with the standard  
195 deviation of the additive flux from each of these profiles, to indicate quantitatively the  
196 uncertainty of CARVE fluxes. For additional details regarding the approach used to  
197 examine CARVE CO<sub>2</sub> observations, please refer to *Henderson et al.* [2015].

### 3. Results

#### 3.1. Site-scale

198 We confronted both PolarVPRM-EVI and PolarVPRM-SIF NEE with site-scale obser-  
199 vations of NEE collected at four established Alaskan eddy covariance sites (2012–2014)  
200 [Table 1]. PolarVPRM-EVI NEE overestimated the timing and magnitude of late winter  
201 photosynthesis at bog, sedge and tussock tundra sites. Unlike SIF, EVI increased during  
202 late winter snowmelt [Figure 1], and remained elevated throughout the late snow season  
203 [Figure S2]. Overall, growing season onset was better captured using PolarVPRM-SIF  
204 than PolarVPRM-EVI at tundra sites [Figure 2].

205 If the carbon uptake period is estimated from EVI, the start of the tundra growing  
206 season is therefore assumed to occur earlier than observed at the site-scale. Since solar  
207 radiation is used to estimate photosynthesis, the coincident timing of the solar maximum,  
208 and snowmelt-induced increases in EVI conspire to result in large overestimates of spring  
209 photosynthesis. Conversely, applying a SIF-based approach enables model estimates to  
210 capture the timing of peak photosynthesis [Figure 2].

### 3.2. Regional

211 A comparison of NEE modeled using SIF and EVI to CARVE-optimized NEE revealed a  
212 tendency for spring photosynthetic uptake to be overestimated when the seasonal cycle was  
213 prescribed using EVI [Figure 3]. Evaluation of daily mean model NEE against daily mean  
214 CARVE NEE indicated that the SIF-based model had a root-mean-square error (RMSE)  
215 of  $0.387 \mu\text{mol m}^{-2} \text{s}^{-1}$ , whereas the EVI-based model had an RMSE of  $0.579 \mu\text{mol m}^{-2} \text{s}^{-1}$ .  
216 CARVE-optimized NEE indicated that the growing season (when weekly  $\text{NEE} < 0$ ) began  
217 on days 160, 167 and 161, in 2012, 2013 and 2014, respectively. Relative to CARVE  
218 data, EVI-based estimates of NEE indicated the growing season to begin 9, 20 and 16  
219 days too early, whereas the SIF-based approach underestimated these dates by only 1, 9  
220 and 8 days. This corresponds to biases of 15 days by PolarVPRM-EVI and 6 days by  
221 PolarVPRM-SIF.

222 GOME-2 SIF more accurately captures the seasonal cycle of tundra photosynthesis  
223 than MODIS EVI. Prescribing a seasonal cycle of photosynthesis using GOME-2 SIF  
224 rather than MODIS EVI resulted in improved agreement between modeled and observed  
225 NEE across Alaska's tundra-dominated regions. Overestimates of tundra photosynthesis  
226 by EVI-driven models result in diminished accuracy in estimates of Alaska's carbon cy-

227 cle [Figure S6], whereas SIF-driven estimates show reasonable agreement with CARVE  
228 observations across Alaska [Figure S5].

## 4. Discussion

### 4.1. SIF captures spring photosynthetic onset better than EVI

229 Whereas EVI represents the presence, quantity or health of aboveground vegetation  
230 [*Wang et al.*, 2002; *Sims et al.*, 2006], from which photosynthetic capacity can be inferred,  
231 SIF occurs as a direct result of light absorption by the chlorophyll complex [*Yang et al.*,  
232 2015; *Frankenberg et al.*, 2014; *Parazoo et al.*, 2013]. SIF is therefore more likely than EVI  
233 to capture the lag between initial spring snowmelt, start of growing season ( $NEE < 0$ ), and  
234 onset of high rates of canopy photosynthesis [*Joiner et al.*, 2014].

235 In snow-dominated regions, EVI can remain elevated ( $> 0$ ) throughout most of the  
236 snow season if canopy height exceeds snow depth, or if influenced by non-vegetation land  
237 surface properties [Figure S2]. In late winter, EVI rises quickly from a non-zero base  
238 value in response to the appearance of senescent vegetation revealed through snowmelt,  
239 and confounding changes over time in non-chlorophyll containing surface properties, rather  
240 than due to leaf out or photosynthetic onset [*Fontana et al.*, 2008; *Jin and Eklundh*, 2014].  
241 The combination of these errors in estimating the seasonal cycle of photosynthesis using  
242 EVI would be difficult to correct fully for across large, heterogeneous and cloudy region  
243 such as Alaska.

244 EVI-driven models can estimate photosynthesis to occur throughout the portion of the  
245 late snow season and early growing season where warm ( $> 0^{\circ}\text{C}$ ) and sunny conditions  
246 prevail. The timing of snowmelt and photosynthesis may initially coincide when ever-  
247 green arctic vegetation rapidly begins to photosynthesize during initial snowmelt while



248 air temperatures and subnivean CO<sub>2</sub> concentrations are high [*Starr and Oberbauer, 2003*].  
249 However, productivity has been observed to stall following snowmelt, and the rate of net  
250 CO<sub>2</sub> efflux has been observed to increase slightly when exposed to freeze-thaw cycles  
251 [*Larsen et al., 2007*]. Without the insulating effect of a dry snowpack, vegetation is likely  
252 to be more vulnerable to cold air temperatures during and following snowmelt, which can  
253 cause damage and disproportionately hinder green-up, leaf-out and photosynthetic onset  
254 [*Bokhorst et al., 2009*]. Relying on EVI for modeling Arctic NEE can therefore result in  
255 overestimates of photosynthetic rates throughout the late snow season and early growing  
256 season.

#### 4.2. Tundra NEE is better captured by SIF than EVI

257 SIF reliably captures the seasonal cycle of tundra photosynthesis, which is consistent  
258 with previous studies of non-Arctic ecosystems (i.e. savannas [*Pérez-Priego et al., 2015*],  
259 rainforests [*Lee et al., 2013*], forests [*Walther et al., 2015*], crops [*Guanter et al., 2014*]). Es-  
260 tablishing the utility of SIF for tundra regions provides further motivation for widespread  
261 application of a SIF-based approach to global carbon cycle modeling.

262 Using SIF, rather than EVI, to estimate tundra NEE enables closer agreement between  
263 modeled and observed NEE due mainly to differences in timing of growing season onset,  
264 and the tendency for SIF to remain near 0 throughout the non-growing season. Similar  
265 seasonal patterns in APAR relative to SIF have been observed in boreal forests [*Joiner*  
266 *et al., 2013*], and we find similar patterns in Alaskan MODIS GPP [*Running and Zhao,*  
267 *2015*] [Figure S6]. Additionally, whereas PolarVPRM-EVI requires scalar terms to reduce  
268 shoulder season photosynthesis and suppress cold season photosynthesis, SIF provides

269 more direct estimates of tundra’s seasonal cycle, and so can be included parsimoniously  
270 in models.

271 Arctic warming caused by climate change can both enable more carbon uptake by high-  
272 latitude vegetation due to a lengthening growing season [*Goetz et al.*, 2005; *Groendahl*  
273 *et al.*, 2007], and increase rates of carbon release from thawing permafrost [*Schuur et al.*,  
274 2008]. Accurately monitoring the Arctic carbon balance is important due to the immense  
275 quantity ( $\approx 1700$  Gt) of soil organic carbon [*Tarnocai et al.*, 2009] underlying Arctic  
276 regions, and positive feedbacks between climate warming and greenhouse gas emissions  
277 from permafrost [*Schuur et al.*, 2015]. Accurately characterizing net carbon uptake by  
278 tundra ecosystems at the regional scale, and monitoring changes over time in growing  
279 season onset and length, are therefore critically important.

### 4.3. SIF-based modeling of tundra NEE

280 Satellite-data-driven estimates of tundra photosynthesis can be calculated empirically  
281 from meteorological observations and SIF, according to site-scale associations between  
282 NEE and meteorology. Accurate model estimates of regional-scale carbon cycling rely  
283 on an appropriate model formulation, parameter fitting, selection of satellite indices, and  
284 processing of satellite inputs to the model.

285 In light of the similarity in estimates of tundra NEE generated from OCO-2 SIF and  
286 GOME-2 SIF, future work may focus on examining the potential to create a blended  
287 product that exploits GOME-2’s longer data record and complete spatial coverage, and  
288 OCO-2’s finer spatial resolution. Further reductions in uncertainty regarding global  
289 photosynthesis will likely also result from combining SIF observations from OCO-2 and  
290 GOME-2 with SIF retrieved by the TROPOspheric Monitoring Instrument (TROPOMI).

291 TROPOMI will have a wide swath, high signal-to-noise ratio, fine spatial resolution in  
292 global composites (0.1 °), and large number of clear-sky observations over land per day  
293 relative to existing products [*Guanter et al.*, 2015].

294 The results presented here also suggest strategies for improving the accuracy of process-  
295 based estimates of high-latitude CO<sub>2</sub> cycling. Regional estimates of CO<sub>2</sub> concentrations  
296 over time by thirteen established process-based models were recently evaluated relative  
297 to atmospheric observations of CO<sub>2</sub> through the International Land Model Benchmark-  
298 ing Project (ILAMB) [*Hoffman et al.*, 2015]. Findings indicated systematic springtime  
299 overestimates of net carbon uptake by vegetation across high-latitude Northern regions  
300 (50–70° N), due in part to an overly early start to the growing season. Photosynthesis  
301 in these process-based models was simulated using strategies resembling both SIF-based  
302 [*Ball et al.*, 1987] and EVI-based [*Roberts et al.*, 2004] approaches. Overestimates of spring  
303 photosynthetic uptake in these models may occur when deciduous growth of photosyn-  
304 thetic tissues or evergreen recovery from cold hardening are simulated to occur faster  
305 than they actually do [*Bergh et al.*, 1998]. Improved accuracy in process-based modeling  
306 of Arctic carbon cycling could therefore potentially be attained by simulating lags be-  
307 tween green-up and growing season onset using tundra-specific stress factors relating to  
308 vegetation photosynthetic capacity.

## 5. Conclusions

309 SIF captures the timing of spring green-up, and seasonal cycle of photosynthesis across  
310 Alaskan tundra. EVI indicates tundra growing season onset to occur an average of nine  
311 days sooner than SIF. EVI-driven estimates of arctic NEE likely estimate growing season  
312 onset to occur too soon, and may overestimate growing season duration [Figure S6].

313 Alaskan tundra carbon cycling can be accurately modeled using an empirical, data-  
314 driven approach integrating satellite observations of SIF, temperature and shortwave  
315 radiation. Prescribing the seasonal cycle of photosynthesis according to SIF enables  
316 accurate modeling of tundra NEE relative to tower and aircraft CO<sub>2</sub> measurements  
317 (RMSE=0.39  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ). Alaskan carbon budget estimates are biased towards too  
318 much uptake if growing season length is prescribed by EVI instead of SIF [Figure S5].

319 Using an SIF-based approach to estimate tundra canopy photosynthesis therefore pro-  
320 vides improved understanding of the extent to which high-latitude regions are taking up  
321 and releasing carbon, and how this is changing over time. SIF-driven modeling of tundra  
322 photosynthesis enables improved constraints on the tundra carbon cycle, and enhanced  
323 understanding of feedbacks between Arctic carbon cycling and climate change.

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*and Lin* [2016].

## References

Ball, J. T., I. E. Woodrow, and J. A. Berry (1987), A model predicting stomatal conduc-  
tance and its contribution to the control of photosynthesis under different environmental  
conditions, in *Progress in photosynthesis research*, pp. 221–224, Springer.

- 355 Barichivich, J., K. R. Briffa, R. B. Myneni, T. J. Osborn, T. M. Melvin, P. Ciais, S. Piao,  
356 and C. Tucker (2013), Large-scale variations in the vegetation growing season and annual  
357 cycle of atmospheric co<sub>2</sub> at high northern latitudes from 1950 to 2011, *Global change*  
358 *biology*, *19*(10), 3167–3183.
- 359 Bergh, J., R. E. McMurtrie, and S. Linder (1998), Climatic factors controlling the pro-  
360 ductivity of norway spruce: a model-based analysis, *Forest ecology and management*,  
361 *110*(1), 127–139.
- 362 Bokhorst, S. F., J. W. Bjerke, H. Tømmervik, T. V. Callaghan, and G. K. Phoenix (2009),  
363 Winter warming events damage sub-Arctic vegetation: consistent evidence from an  
364 experimental manipulation and a natural event, *Journal of Ecology*, *97*(6), 1408–1415.
- 365 Chang, R. Y.-W., C. E. Miller, S. J. Dinardo, A. Karion, C. Sweeney, B. C. Daube,  
366 J. M. Henderson, M. E. Mountain, J. Eluszkiewicz, J. B. Miller, et al. (2014), Methane  
367 emissions from Alaska in 2012 from CARVE airborne observations, *Proceedings of the*  
368 *National Academy of Sciences*, *111*(47), 16,694–16,699.
- 369 Chapin III, F. (1983), Direct and indirect effects of temperature on arctic plants, *Polar*  
370 *Biology*, *2*(1), 47–52.
- 371 Euskirchen, E., M. S. Bret-Harte, G. Scott, C. Edgar, and G. R. Shaver (2012), Seasonal  
372 patterns of carbon dioxide and water fluxes in three representative tundra ecosystems  
373 in northern Alaska, *Ecosphere*, *3*(1), art4.
- 374 Euskirchen, E., C. Edgar, M. Turetsky, M. Waldrop, and J. Harden (2014), Differential  
375 response of carbon fluxes to climate in three peatland ecosystems that vary in the  
376 presence and stability of permafrost, *Journal of Geophysical Research: Biogeosciences*,  
377 *119*(8), 1576–1595.

- 378 Fontana, F., C. Rixen, T. Jonas, G. Aberegg, and S. Wunderle (2008), Alpine grass-  
379 land phenology as seen in AVHRR, VEGETATION, and MODIS NDVI time series-a  
380 comparison with in situ measurements, *Sensors*, *8*(4), 2833–2853.
- 381 Frankenberg, C., J. B. Fisher, J. Worden, G. Badgley, S. S. Saatchi, J.-E. Lee, G. C. Toon,  
382 A. Butz, M. Jung, A. Kuze, et al. (2011a), New global observations of the terrestrial  
383 carbon cycle from gosat: Patterns of plant fluorescence with gross primary productivity,  
384 *Geophysical Research Letters*, *38*(17).
- 385 Frankenberg, C., A. Butz, and G. C. Toon (2011b), Disentangling chlorophyll fluores-  
386 cence from atmospheric scattering effects in O2 A-band spectra of reflected sun-light,  
387 *Geophysical Research Letters*, *38*(3), doi:10.1029/2010GL045896, 103801.
- 388 Frankenberg, C., C. O’Dell, J. Berry, L. Guanter, J. Joiner, P. Köhler, R. Pollock, and  
389 T. E. Taylor (2014), Prospects for chlorophyll fluorescence remote sensing from the  
390 Orbiting Carbon Observatory-2, *Remote Sensing of Environment*, *147*, 1–12.
- 391 Goetz, S. J., A. G. Bunn, G. J. Fiske, and R. Houghton (2005), Satellite-observed photo-  
392 synthetic trends across boreal North America associated with climate and fire distur-  
393 bance, *Proceedings of the National Academy of Sciences of the United States of America*,  
394 *102*(38), 13,521–13,525.
- 395 Groendahl, L., T. Friborg, and H. Sogaard (2007), Temperature and snow-melt controls  
396 on interannual variability in carbon exchange in the high arctic, *Theoretical and Applied*  
397 *Climatology*, *88*(1-2), 111–125.
- 398 Guanter, L., Y. Zhang, M. Jung, J. Joiner, M. Voigt, J. A. Berry, C. Frankenberg, A. R.  
399 Huete, P. Zarco-Tejada, J.-E. Lee, et al. (2014), Global and time-resolved monitoring of  
400 crop photosynthesis with chlorophyll fluorescence, *Proceedings of the National Academy*

- 401 *of Sciences*, 111(14), E1327–E1333.
- 402 Guanter, L., I. Aben, P. Tol, J. Krijger, A. Hollstein, P. Köhler, A. Damm, J. Joiner,  
403 C. Frankenberg, and J. Landgraf (2015), Potential of the TROPospheric Monitoring  
404 Instrument (TROPOMI) onboard the Sentinel-5 Precursor for the monitoring of terres-  
405 trial chlorophyll fluorescence, *Atmospheric Measurement Techniques*, 8, 1337–1352.
- 406 Hall, D. K., G. A. Riggs, V. V. Salomonson, N. E. DiGirolamo, and K. J. Bayr (2002),  
407 MODIS snow-cover products, *Remote sensing of Environment*, 83(1), 181–194.
- 408 Henderson, J., J. Eluszkiewicz, M. Mountain, T. Nehr Korn, R. Chang, A. Karion, J. Miller,  
409 C. Sweeney, N. Steiner, S. Wofsy, et al. (2015), Atmospheric transport simulations in  
410 support of the Carbon in Arctic Reservoirs Vulnerability Experiment (CARVE), *Atmos*  
411 *Chem Phys*, 15(8), 4093–4116.
- 412 Hoffman, F. M., W. J. Riley, J. T. Randerson, S. M. Elliott, G. Keppel-Aleks, C. D.  
413 Koven, D. M. Lawrence, U. Mishra, J. K. Moore, and X. Yang (2015), Biogeochemistry–  
414 climate feedbacks: Quantifying feedbacks and uncertainties of biogeochemical processes  
415 in Earth System Models.
- 416 Huete, A., C. Justice, and W. Van Leeuwen (1999), MODIS vegetation index (MOD13),  
417 *Algorithm theoretical basis document*, 3, 213.
- 418 Jin, H., and L. Eklundh (2014), A physically based vegetation index for improved moni-  
419 toring of plant phenology, *Remote Sensing of Environment*, 152, 512–525.
- 420 Joiner, J., L. Guanter, R. Lindstrot, M. Voigt, A. Vasilkov, E. Middleton, K. Huemm-  
421 rich, Y. Yoshida, and C. Frankenberg (2013), Global monitoring of terrestrial chloro-  
422 phyll fluorescence from moderate-spectral-resolution near-infrared satellite measure-  
423 ments: methodology, simulations, and application to GOME-2, *Atmospheric Measure-*



- 424 *ment Techniques*, 6(10), 2803–2823.
- 425 Joiner, J., Y. Yoshida, A. Vasilkov, K. Schaefer, M. Jung, L. Guanter, Y. Zhang, S. Gar-  
426 rity, E. Middleton, K. Huemmrich, et al. (2014), The seasonal cycle of satellite chloro-  
427 phyll fluorescence observations and its relationship to vegetation phenology and ecosys-  
428 tem atmosphere carbon exchange, *Remote Sensing of Environment*, 152, 375–391.
- 429 Joiner, J., Y. Yoshida, L. Guanter, and E. M. Middleton (In Press), New methods for  
430 retrieval of chlorophyll red fluorescence from hyper-spectral satellite instruments: sim-  
431 ulations and application to GOME-2 and SCIAMACHY, *Atmospheric Measurement*  
432 *Techniques Discussions*, pp. doi:10.5194/amt-2015-387.
- 433 Jung, M., K. Henkel, M. Herold, and G. Churkina (2006), Exploiting synergies of global  
434 land cover products for carbon cycle modeling, *Remote Sensing of Environment*, 101(4),  
435 534–553.
- 436 Karion, A., C. Sweeney, S. Wolter, T. Newberger, H. Chen, A. Andrews, J. Kofler, D. Neff,  
437 and P. Tans (2013), Long-term greenhouse gas measurements from aircraft, *Atmospheric*  
438 *Measurement Techniques*, 6(3), 511–526.
- 439 Karion, A., C. Sweeney, J. B. Miller, A. E. Andrews, R. Commane, S. Dinardo, J. M.  
440 Henderson, J. Lindaas, J. C. Lin, K. A. Luus, T. Newberger, P. Tans, S. C. Wofsy,  
441 S. Wolter, and C. E. Miller (2016), Investigating Alaskan methane and carbon diox-  
442 ide fluxes using measurements from the CARVE tower, *Atmospheric Chemistry and*  
443 *Physics*, 16(8), 5383–5398, doi:10.5194/acp-16-5383-2016.
- 444 Kwon, H.-J., W. C. Oechel, R. C. Zulueta, and S. J. Hastings (2006), Effects of climate  
445 variability on carbon sequestration among adjacent wet sedge tundra and moist tussock  
446 tundra ecosystems, *Journal of Geophysical Research: Biogeosciences*, 111(G3).

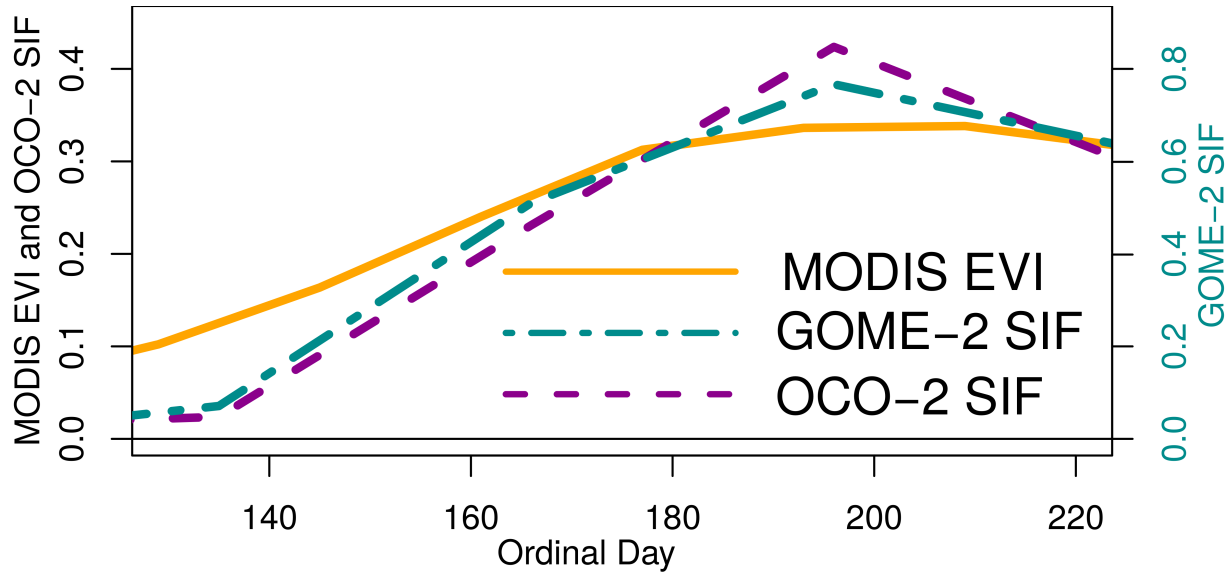
- 447 Larsen, K. S., A. Ibrom, S. Jonasson, A. Michelsen, and C. Beier (2007), Significance of  
448 cold-season respiration and photosynthesis in a subarctic heath ecosystem in Northern  
449 Sweden, *Global Change Biology*, *13*(7), 1498–1508.
- 450 Lee, J.-E., C. Frankenberg, C. van der Tol, J. A. Berry, L. Guanter, C. K. Boyce, J. B.  
451 Fisher, E. Morrow, J. R. Worden, S. Asefi, et al. (2013), Forest productivity and water  
452 stress in Amazonia: observations from GOSAT chlorophyll fluorescence, *Proceedings of*  
453 *the Royal Society of London B: Biological Sciences*, *280*(1761), 20130,171.
- 454 Lin, J., C. Gerbig, S. Wofsy, A. Andrews, B. Daube, K. Davis, and C. Grainger (2003), A  
455 near-field tool for simulating the upstream influence of atmospheric observations: The  
456 stochastic time-inverted lagrangian transport (STILT) model, *Journal of Geophysical*  
457 *Research: Atmospheres* (1984–2012), *108*(D16).
- 458 Lipson, D. A., D. Zona, T. K. Raab, F. Bozzolo, M. Mauritz, and W. C. Oechel (2012),  
459 Water table height and microtopography control biogeochemical cycling in an arctic  
460 coastal tundra ecosystem, *Biogeosciences*, *9*, 577–591.
- 461 Luus, K., and J. Lin (2015), The Polar Vegetation Photosynthesis and Respiration Model  
462 (PolarVPRM): a parsimonious, satellite data-driven model of high-latitude CO<sub>2</sub> ex-  
463 change, *Geoscientific Model Development*, *8*(2), 979–1027.
- 464 Luus, K., and J. Lin (2016), CARVE Modeled Gross Ecosystem CO<sub>2</sub> Exchange and  
465 Respiration, Alaska, 2012-2014, <http://dx.doi.org/10.3334/ORNLDAAC/1314>.
- 466 Luus, K., Y. Gel, J. Lin, R. Kelly, and C. Duguay (2013a), Pan-Arctic linkages between  
467 snow accumulation and growing-season air temperature, soil moisture and vegetation,  
468 *Biogeosciences*, *10*, 7575–7597.

- 469 Luus, K., R. Kelly, J. Lin, E. Humphreys, P. Lafleur, and W. Oechel (2013b), Modeling the  
470 influence of snow cover on low Arctic net ecosystem exchange, *Environmental Research*  
471 *Letters*, 8(3), 035,045.
- 472 Luus, K. A., J. C. Lin, R. E. Kelly, and C. R. Duguay (2013c), Subnivean Arctic and sub-  
473 Arctic net ecosystem exchange (NEE): towards representing snow season processes in  
474 models of Nee using cryospheric remote sensing, *Progress in Physical Geography*, 37(4),  
475 484–515.
- 476 Mahadevan, P., S. C. Wofsy, D. M. Matross, X. Xiao, A. L. Dunn, J. C. Lin, C. Ger-  
477 big, J. W. Munger, V. Y. Chow, and E. W. Gottlieb (2008), A satellite-based biosphere  
478 parameterization for net ecosystem CO<sub>2</sub> exchange: Vegetation Photosynthesis and Res-  
479 piration Model (VPRM), *Global Biogeochemical Cycles*, 22(2).
- 480 Mesinger, F., G. DiMego, E. Kalnay, K. Mitchell, P. C. Shafran, W. Ebisuzaki, D. Jovic,  
481 J. Woollen, E. Rogers, E. H. Berbery, et al. (2006), North American regional reanalysis,  
482 *Bulletin of the American Meteorological Society*, 87(3), 343–360.
- 483 Miller, C. E., and S. J. Dinardo (2012), CARVE: The Carbon in arctic reservoirs vulner-  
484 ability experiment, in *Aerospace conference, 2012 IEEE*, pp. 1–17, IEEE.
- 485 (MODAPS), M. L. S. T. A. P. S. (2016), MODIS/Terra Atmospheri-  
486 cally Corrected Surface Reflectance 5Min L2 Swath 250m 500m 1km,  
487 <http://dx.doi.org/10.5067/MODIS/MOD09.NRT.006>.
- 488 O’Sullivan, O. S., M. A. Heskell, P. B. Reich, M. G. Tjoelker, K. L. K. Weerasinghe,  
489 A. Penillard, L. Zhu, J. J. Egerton, K. J. Bloomfield, D. Creek, N. H. A. Bahar, K. L.  
490 Griffin, V. Hurry, P. Meir, M. H. Turnbull, and O. K. Atkin (2016), Thermal limits of leaf  
491 metabolism across biomes, *Global Change Biology*, pp. n/a–n/a, doi:10.1111/gcb.13477.

- 492 Parazoo, N. C., K. Bowman, C. Frankenberg, J.-E. Lee, J. B. Fisher, J. Worden, D. Jones,  
493 J. Berry, G. J. Collatz, I. T. Baker, et al. (2013), Interpreting seasonal changes in the  
494 carbon balance of southern Amazonia using measurements of XCO<sub>2</sub> and chlorophyll  
495 fluorescence from GOSAT, *Geophysical Research Letters*, *40*(11), 2829–2833.
- 496 Pérez-Priego, O., J.-H. Guan, M. Rossini, F. Fava, T. Wutzler, G. Moreno, N. Carvalhais,  
497 A. Carrara, O. Kolle, T. Julitta, et al. (2015), Sun-induced chlorophyll fluorescence and  
498 photochemical reflectance index improve remote-sensing gross primary production esti-  
499 mates under varying nutrient availability in a typical Mediterranean savanna ecosystem,  
500 *Biogeosciences*, *12*, 6351–6367.
- 501 Porcar-Castell, A., E. Tyystjärvi, J. Atherton, C. van der Tol, J. Flexas, E. E. Pfündel,  
502 J. Moreno, C. Frankenberg, and J. A. Berry (2014), Linking chlorophyll a fluorescence  
503 to photosynthesis for remote sensing applications: mechanisms and challenges, *Journal*  
504 *of Experimental Botany*, p. eru191.
- 505 R Core Team (2013), *R: A Language and Environment for Statistical Computing*, R Foun-  
506 dation for Statistical Computing, Vienna, Austria.
- 507 Roberts, D. A., S. L. Ustin, S. Ogunjemiyo, J. Greenberg, S. Z. Dobrowski, J. Chen, and  
508 T. M. Hinckley (2004), Spectral and structural measures of northwest forest vegetation  
509 at leaf to landscape scales, *Ecosystems*, *7*(5), 545–562.
- 510 Running, S. W., and M. Zhao (2015), Daily GPP and Annual NPP (MOD17A2/A3)  
511 products NASA Earth Observing System MODIS land algorithm.
- 512 Schuur, E., A. McGuire, C. Schädel, G. Grosse, J. Harden, D. Hayes, G. Hugelius,  
513 C. Koven, P. Kuhry, D. Lawrence, et al. (2015), Climate change and the permafrost  
514 carbon feedback, *Nature*, *520*(7546), 171–179.

- 515 Schuur, E. A., J. Bockheim, J. G. Canadell, E. Euskirchen, C. B. Field, S. V. Goryachkin,  
516 S. Hagemann, P. Kuhry, P. M. Lafleur, H. Lee, et al. (2008), Vulnerability of permafrost  
517 carbon to climate change: implications for the global carbon cycle, *BioScience*, 58(8),  
518 701–714.
- 519 Sims, D. A., A. F. Rahman, V. D. Cordova, B. Z. El-Masri, D. D. Baldocchi, L. B.  
520 Flanagan, A. H. Goldstein, D. Y. Hollinger, L. Misson, R. K. Monson, et al. (2006),  
521 On the use of MODIS EVI to assess gross primary productivity of North American  
522 ecosystems, *Journal of Geophysical Research: Biogeosciences (2005–2012)*, 111(G4).
- 523 Starr, G., and S. F. Oberbauer (2003), Photosynthesis of arctic evergreens under snow:  
524 implications for tundra ecosystem carbon balance, *Ecology*, 84(6), 1415–1420.
- 525 Tarnocai, C., J. Canadell, E. Schuur, P. Kuhry, G. Mazhitova, and S. Zimov (2009), Soil  
526 organic carbon pools in the northern circumpolar permafrost region, *Global biogeochem-  
527 ical cycles*, 23(2).
- 528 Tieszen, L. L. (1973), Photosynthesis and respiration in arctic tundra grasses: field light  
529 intensity and temperature responses, *Arctic and Alpine Research*, pp. 239–251.
- 530 Walker, D. A., M. K. Raynolds, F. J. Daniëls, E. Einarsson, A. Elvebakk, W. A. Gould,  
531 A. E. Katenin, S. S. Kholod, C. J. Markon, E. S. Melnikov, et al. (2005), The circum-  
532 polar arctic vegetation map, *Journal of Vegetation Science*, 16(3), 267–282.
- 533 Walther, S., M. Voigt, T. Thum, A. Gonsamo, Y. Zhang, P. Koehler, M. Jung, A. Varlagin,  
534 and L. Guanter (2015), Satellite chlorophyll fluorescence measurements reveal large-  
535 scale decoupling of photosynthesis and greenness dynamics in boreal evergreen forests,  
536 *Global change biology*.

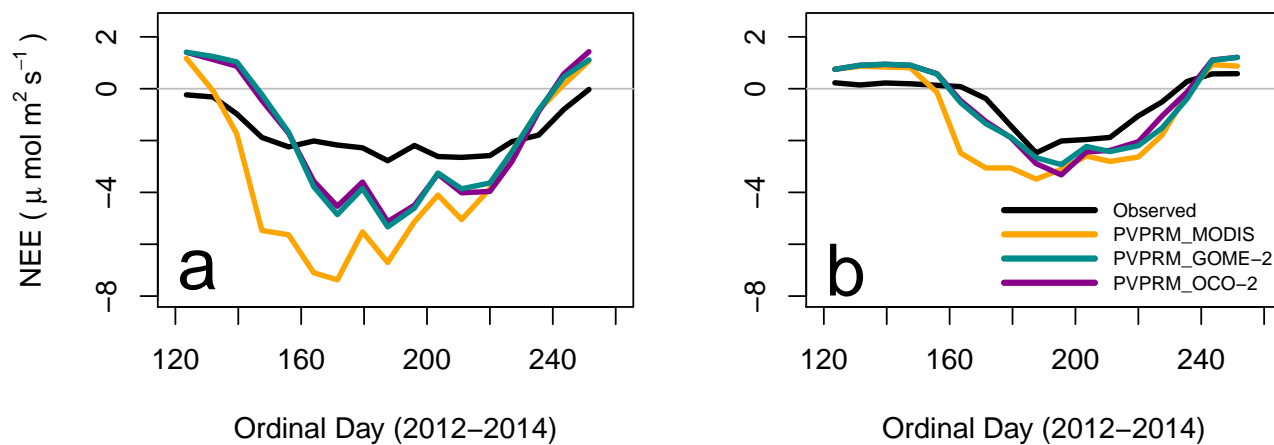
- 537 Wang, X., S. Piao, X. Xu, P. Ciais, N. MacBean, R. B. Myneni, and L. Li (2015), Has the  
538 advancing onset of spring vegetation green-up slowed down or changed abruptly over  
539 the last three decades?, *Global Ecology and Biogeography*, *24*(6), 621–631.
- 540 Wang, Z., C. Liu, and A. Huete (2002), From AVHRR-NDVI to MODIS-EVI: advances  
541 in vegetation index research, *Acta ecologica sinica*, *23*(5), 979–987.
- 542 Yang, X., J. Tang, J. F. Mustard, J.-E. Lee, M. Rossini, J. Joiner, J. W. Munger, A. Korn-  
543 feld, and A. D. Richardson (2015), Solar-induced chlorophyll fluorescence that correlates  
544 with canopy photosynthesis on diurnal and seasonal scales in a temperate deciduous for-  
545 est, *Geophysical Research Letters*, *42*(8), 2977–2987.



**Figure 1.** Spatially averaged 2014 seasonal cycle of MODIS EVI, OCO-2 SIF/ $\cos(\text{solar zenith angle})$  and GOME-2 SIF/ $\cos(\text{SZA})$  across Alaskan tundra.

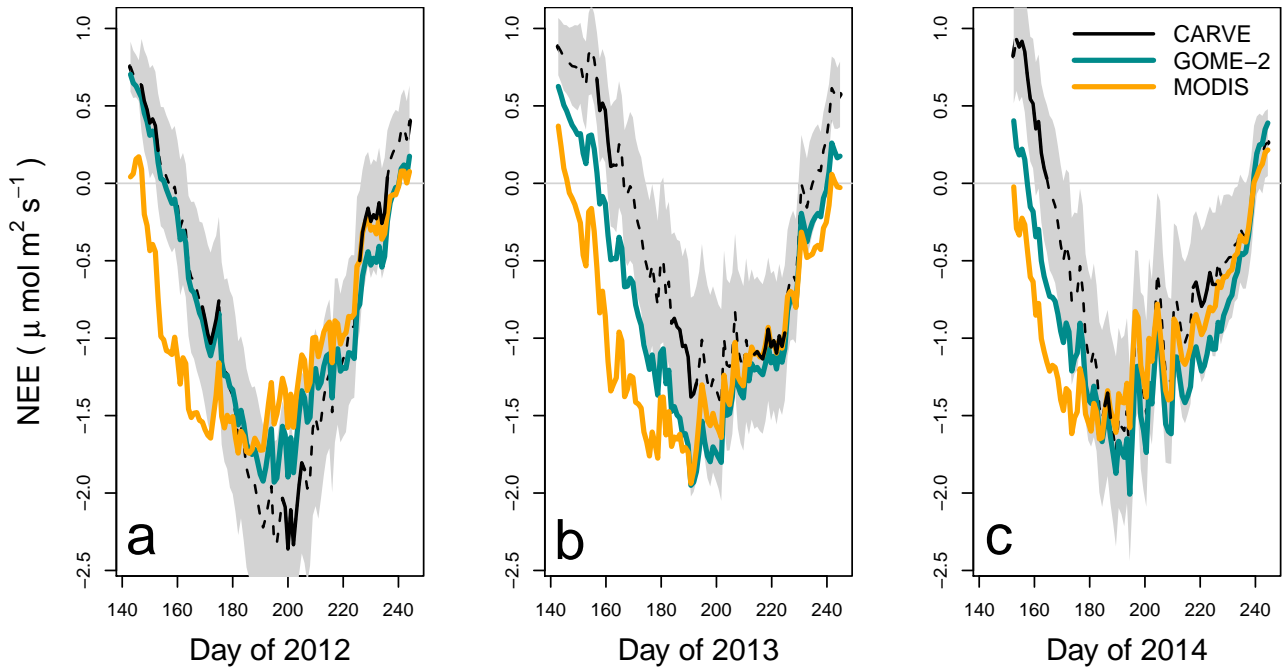
Site	Latitude (° N)	Longitude (° W)	Vegetation	Ref.
Atqasuk	70.470	157.409	Moist-wet sedge	<i>Kwon et al.</i> [2006]
Barrow	71.323	156.626	Wet sedge tundra	<i>Lipson et al.</i> [2012]
Bonanza	64.701	148.321	Thermokarst bog	<i>Euskirchen et al.</i> [2014]
Imnavait	68.606	149.304	Wet tussock/sedge tundra	<i>Euskirchen et al.</i> [2012]

**Table 1.** Eddy covariance site descriptions



**Figure 2.** Time series (2012–2014) of mean eddy covariance NEE, EVI-based NEE, and SIF-based NEE at the Bonanza Creek thermokarst bog (a) and Imnavait wet sedge (b) sites, described in Table 1.





**Figure 3.** Spatially averaged Alaskan tundra NEE simulated using MODIS EVI and GOME-2 SIF, and CARVE-optimized NEE across Alaskan tundra in 2012 (a), 2013 (b) and 2014 (c). In all plots, the time series of mean CARVE-optimized NEE from 273 column profiles is indicated with a solid black line, interpolated NEE is indicated with a dotted line, and the standard deviation of the additive flux from CARVE column profiles is indicated in grey.

**Table 2.** Parameter values for all models (MODIS EVI, GOME-2 SIF and OCO-2 SIF).  $T_{\min}=0^{\circ}\text{C}$  and  $T_{\max}=40^{\circ}\text{C}$  for all models and vegetation classes [Figure S4].

Param	Model	Evgrn. Forest	Decid. Forest	Mixed Forest	Shrubs	Shrub Tundra	Graminoid Tun.	Wetland
$\lambda$	MODIS	0.234	0.127	0.123	0.122	0.040	0.030	0.149
$\lambda$	GOME-2	0.065	0.040	0.035	0.038	0.020	0.014	0.072
$\lambda$	OCO-2	0.117	0.061	0.064	0.064	0.046	0.028	0.160
$\text{PAR}_0$	All	262	570	629	321	241	241	241
$T_{opt}$	All	20	20	20	20	15	15	10