

Global Biogeochemical Cycles

Supporting Information for

Annual cycles of phytoplankton biomass in the Subarctic Atlantic and Pacific Ocean

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Introduction

The supporting information in this document provides additional details regarding autonomous profiling float data, comparison of satellite Chl and C_{phyto} with field data, annual cycles of alternative satellite ocean color products, and a synoptic look at a natural iron fertilization event in the subarctic northeast Pacific. Each is described in its own section (Text S1-4) and additional references are also given (Text S5). There are also five supporting figures (S5), that roughly correspond to each supporting text section.

Text S1.

Autonomous profiling float data

Measurements of Chl, C_{phyto}, and NO₃ were collected from autonomous profiling floats in the NPac. The general characteristics (profiling frequency, sampling depths, parameters measured, etc.) of the primary float (SN 4738) are described in the main manuscript. A map of its drift track shows the proximity and overlap of the study area (Figure S1a, red line). Four additional floats were also used to better resolve the annual cycles shown in Figure 3b and 8a of the main manuscript. These data were downloaded from the Monterey Bay Aquarium Research Institute Chemical Sensor Program (<http://www.mbari.org/chemsensor/floatviz.htm>). Here, we use the long-term record of deep-water bio-optical properties to demonstrate the lack of significant instrumental drift (Figure S1b). For example, Chl averaged over 900-1000 meters during the first 40 profiles (~Feb-Jun 2010) was $0.007 \pm 0.006 \text{ mgChl m}^{-3}$ and during last 40 profiles (~Aug-Dec 2013) was $0.006 \pm 0.007 \text{ mgChl m}^{-3}$. These values are approximately 2-3% of surface Chl. bbp443 over the same depth range during the first 40 profiles was $3.8 \pm 0.2 \times 10^{-4} \text{ m}^{-1}$ and during last 40 profiles was $3.4 \pm 0.1 \times 10^{-4} \text{ m}^{-1}$. Time-series of MODISA Chl in the study region generally compares well with float estimates, but float-derived Chl shows much more variability (Figure S1c). Float-derived Chl also systematically suggests higher values during the late summer period of August-October ($\text{Chl}_{\text{float}} = 0.53 \pm 0.18 \text{ mg m}^{-3}$, $\text{Chl}_{\text{MODISA}} = 0.26 \pm 0.08 \text{ mg m}^{-3}$). This mismatch is not found in float and MODISA estimates of C_{phyto} (Figure 3a and 3c of main manuscript)

Text S2.

Variability in satellite climatologies and *in situ* field data

The annual patterns of satellite retrieved chlorophyll (Chl) and phytoplankton carbon biomass (C_{phyto}) in the subarctic North Atlantic and Pacific Ocean are reproduced in Figure S2, but with 2 additional pieces of information. First, upper and lower bounds corresponding to nearly the full range of values encountered in the $5^\circ \times 10^\circ$ regions over the 10 year time period (2003-2012) are indicated. Specifically, Figure S2 shows the 5th and 95th percentile of the distribution at each 8-day interval and demonstrates the much larger potential range for individual, pixel-level estimates of Chl and C_{phyto}. Also shown together with estimates of C_{phyto} in both NATl and NPac basins are some of the few comparable field measurements of phytoplankton biomass. These are not direct determinations of carbon content, but rather conversions of biovolume estimates from microscopic enumeration and sizing of phytoplankton samples.

Data from the subarctic Pacific are reproduced from [Booth *et al.*, 1993] (see their Table 3) and represent samples collected at OSP and a nearby station (145°W, 53°N) during May and August of both 1984 and 1988, and June and September of 1987 (filled grey triangles in Figures S2c). Field phytoplankton carbon data represent average values over the top 60 m of the water column. In contrast, satellite data are based on

water leaving radiances from the upper first attenuation depth, double exponentially weighted toward the surface. This difference is of little importance when mixing depths exceed 60 meters, but in many cases vertical structure in phytoplankton carbon data presented by *Booth et al.* [1993] indicate that the upper water column was not homogeneous, often with carbon concentrations decreasing with depth (Figure 9 in *Booth et al.* [1993]). In such cases, averaging over a 60 m interval will underestimate phytoplankton biomass in the satellite-sensed layer. In comparison with high-resolution eight-day satellite data, we find that some of the field C_{phyto} data fall below the satellite range, particularly in the most-stratified period of the summer. [Savidge *et al.*, 1995] measured phytoplankton carbon (also from biovolume conversions) near the JGOFS NABE site over a six-week period in May and June 1990. Samples were collected every ~3 days at a depth of 10 m while following a drogued buoy. Biomass values ranged from 32 mg m^{-3} to 108 mg m^{-3} (filled grey triangles in Figures S2c).

Text S3.

Response of NPac to Mt. Kasatochi eruption in August 2008

A major volcanic eruption influenced the ocean-atmosphere system of the NPac in August 2008 [Langmann *et al.*, 2010]. Some aspects of the ocean biological response have been documented [Lindenthal *et al.*, 2013; Olgun *et al.*, 2013], including unprecedented values of satellite Chl in the region [Hamme *et al.*, 2010]. Bearing in mind the discussion of phytoplankton physiological impacts on Chl, we examined the patterns of C_{phyto} and C:Chl during this period (Figure S3). Widespread positive anomalies (relative to the climatological averages) in both Chl and C_{phyto} are seen throughout the subarctic NPac, particularly when compared with observed anomalies in previous years (Figure S3; see also Hamme *et al.*, [2010]). Biomass anomalies during this event are nearly as large as the seasonal increase ($\sim 30 \text{ mgC m}^{-3}$), but anomalies in pigment concentration are even larger. The resulting C:Chl over the region exhibits significantly depressed values ($\sim 25\text{-}50 \text{ mgC mgChl}^{-1}$) relative to the 10-year MODISA average (2003-2012, Figure S3). These responses are consistent with similar analyses of natural iron fertilization and mesoscale iron enrichment experiments [Westberry *et al.*, 2013] and further demonstrate the effects of iron on C:Chl retrieved from satellite.

Text S4.

Additional annual cycles in the NATl and NPac

In order to account for photoacclimation in the observed satellite chlorophyll fluorescence records, we have used estimates of the light saturation parameter, E_k , in the NATl and NPac. E_k is predicted from (and linearly proportional to) C:Chl using the model of [Behrenfeld *et al.*, 2015]. Details and caveats of the model are not critical for this application, but annual patterns in both basins are similar to C:Chl presented in Figure 4c of the main manuscript. Phytoplankton are [relatively] high-light acclimated ($E_k \sim 60\text{-}80 \mu\text{Ein m}^{-2} \text{ s}^{-1}$) during the northern hemisphere summer when incident light is high and mixed layer depths are shallow (Figure S4). During the winter, phytoplankton are acclimated to lower light intensities ($E_k \sim 40 \mu\text{Ein m}^{-2} \text{ s}^{-1}$). The modest difference between the NATl and NPac during the spring/summer is likely due to self-shading (peak pigment concentrations occur in the NATl at this time) and thus, slightly lower acclimation irradiances in the NATl.

The annual cycles of net primary production (NPP, $\text{mgC m}^{-2} \text{ d}^{-1}$) and associated phytoplankton growth rate ($\square$, d^{-1}) were estimated using the Carbon-based Production

Model (CbPM) (Figure 7 of main manuscript). We tested the sensitivity of these results to the specific NPP model by repeating the calculations using the Vertically Generalized Production Model (VGPM, [Behrenfeld and Falkowski, 1997]). The VGPM predicts higher NPP than the CbPM across the whole year in both basins (Figure S5a). This finding is consistent with the VGPM's inability to assign a portion of the Chl to photoacclimation. Nevertheless the temporal patterns in NPP are similar, regardless of which model is used. Both models show NPP maxima in June and late August and minima in January and December in the NATl and NPac, respectively. Peak values in the NATl differ by ~50% (VGPM NPP ~ 1200 mgC m⁻² d⁻¹ and CbPM NPP ~ 800 mgC m⁻² d⁻¹), but relative differences during the winter are even greater. This finding may also be related to lower-light acclimation of the wintertime phytoplankton population and the CbPM's assignment of this Chl to physiology. Differences in NPac NPP estimates are not quite as large except during the winter, although estimated rates are low in both cases (NPP < 175 mgC m⁻² d⁻¹). It should be noted here that the CbPM may underestimate NPP in the NATl during light-limited months where extremely deep mixing is interpreted as excessive photoacclimation. Under these circumstances, the model will attribute too much Chl variability to physiology, and not biomass or NPP [Behrenfeld et al., 2015; Westberry et al., 2008]. This will tend to underestimate μ and indeed, μ estimated from VGPM NPP are significantly higher (~0.2 d⁻¹) during the winter (Figure S5b).

Text S5.

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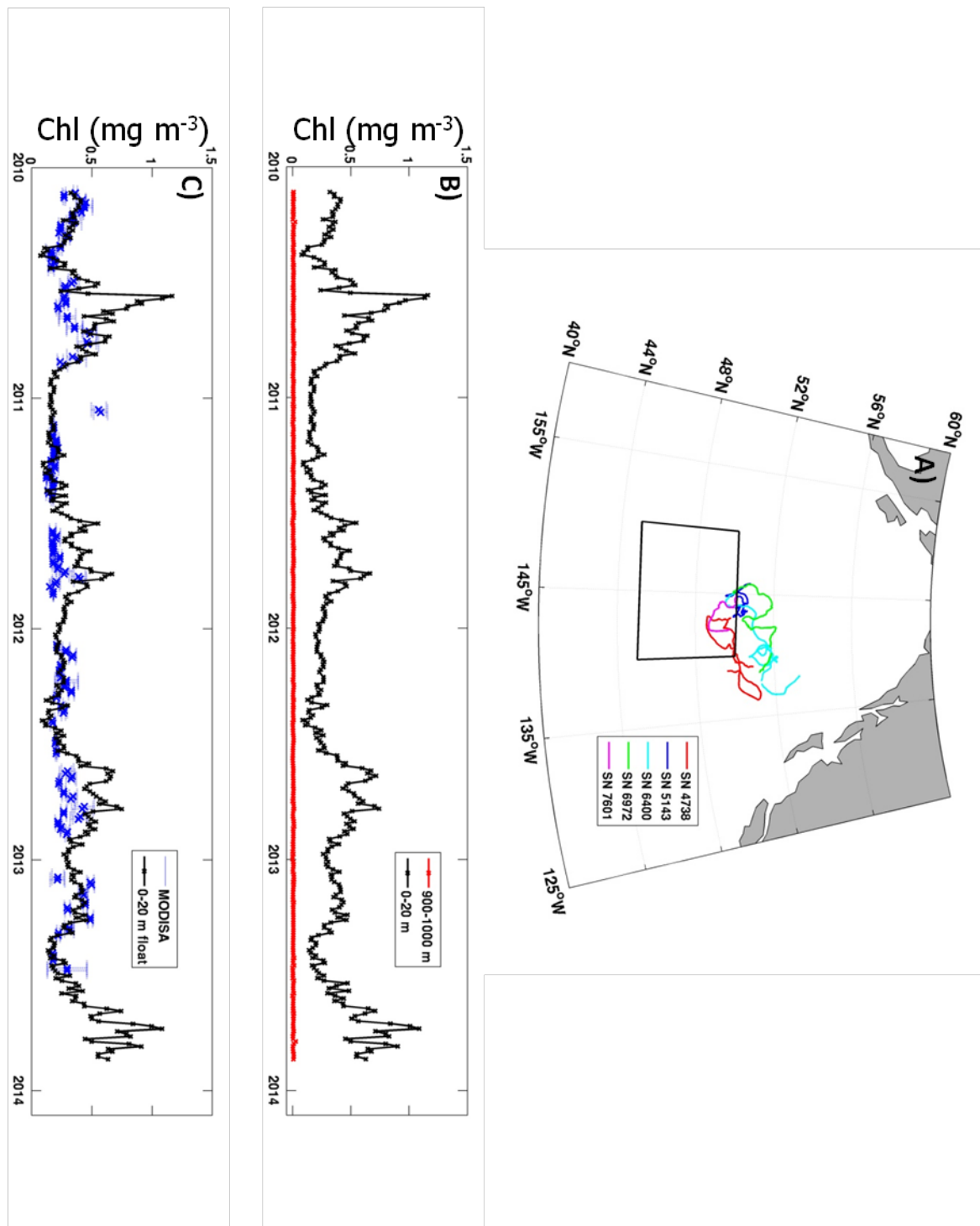


Figure S1. Autonomous profiling float measurements in the NPac. A) Individual float trajectories. Float SN 4738 (red line) is the primary data source used throughout this manuscript, and shown below. Drift tracks of additional floats used are shown as all other colored lines. Outlined box is 5°x10° region used for analysis of annual cycles. B) Time-series of float-derived Chl near the sea surface (0-20 m, black line) and at depth (900-1000 m, red line). C) Matchup of float-derived Chl (black line) with 8-day MODISA Chl (blue symbols) where available. Vertical errorbars represent variability within 5°x10° box described above.

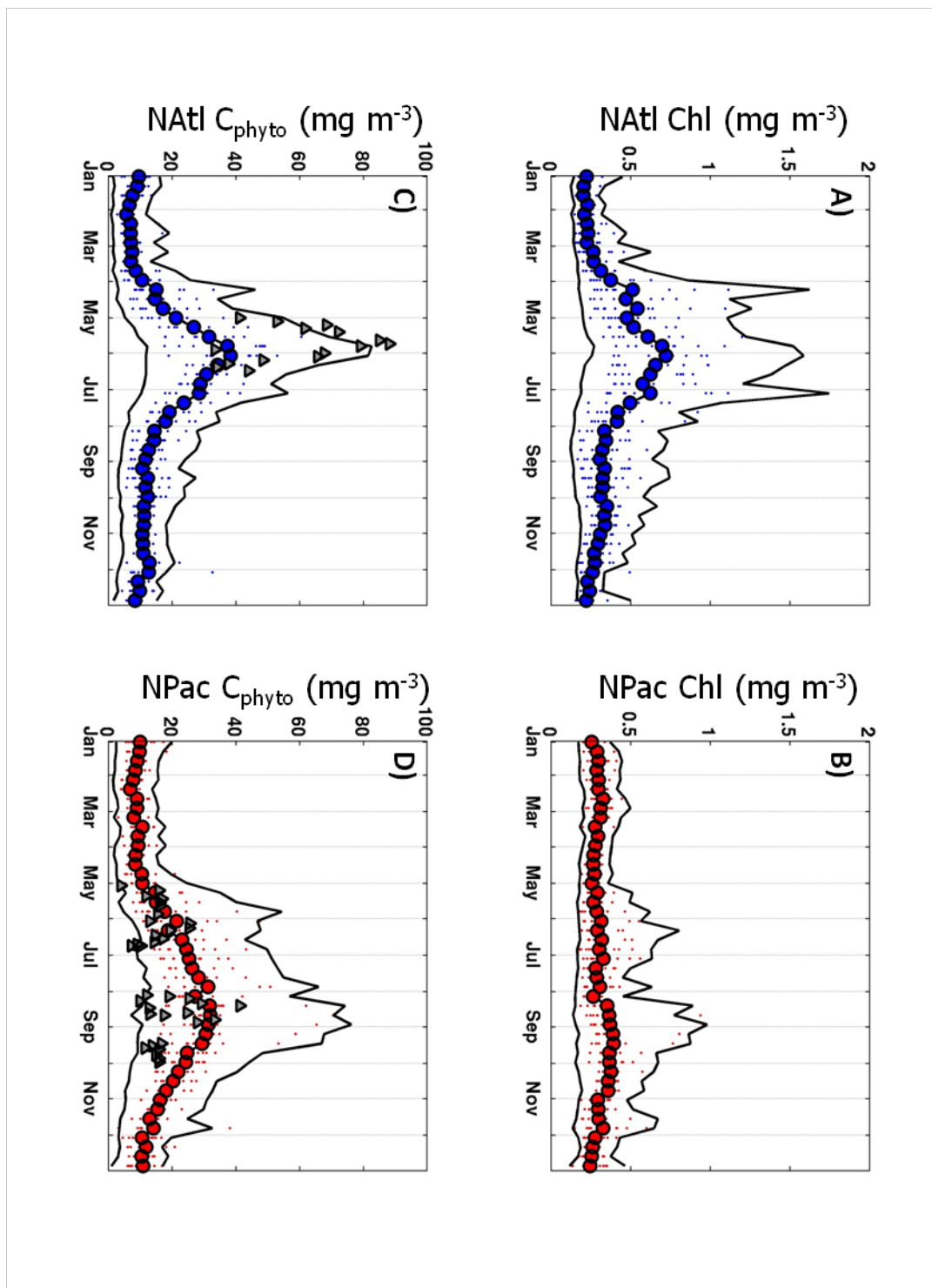


Figure S2. Interannual and within-bin variability in 8-day satellite Chl and C_{phyto} . A) Average annual cycle of Chl in the NAtl (filled blue circles) reproduced as in the main manuscript. Solid black lines represent 5th and 95th percentile (lower and upper lines, respectively) of distribution at each 8-day interval. Number of points at each 8-day interval is $\sim 10^3$ - 10^4 . B) Same as above, but for Chl in the NPac. C) Annual cycle of C_{phyto} in the NAtl. Symbols and lines same as above. Also shown are field estimates of C_{phyto} (gray filled triangles) taken from *Savidge et al. [1995]*. D) Annual cycle of C_{phyto} in the NPac. Symbols and lines same as above. Also shown are field estimates of C_{phyto} (gray filled triangles) taken from *Booth et al. [1993]*.

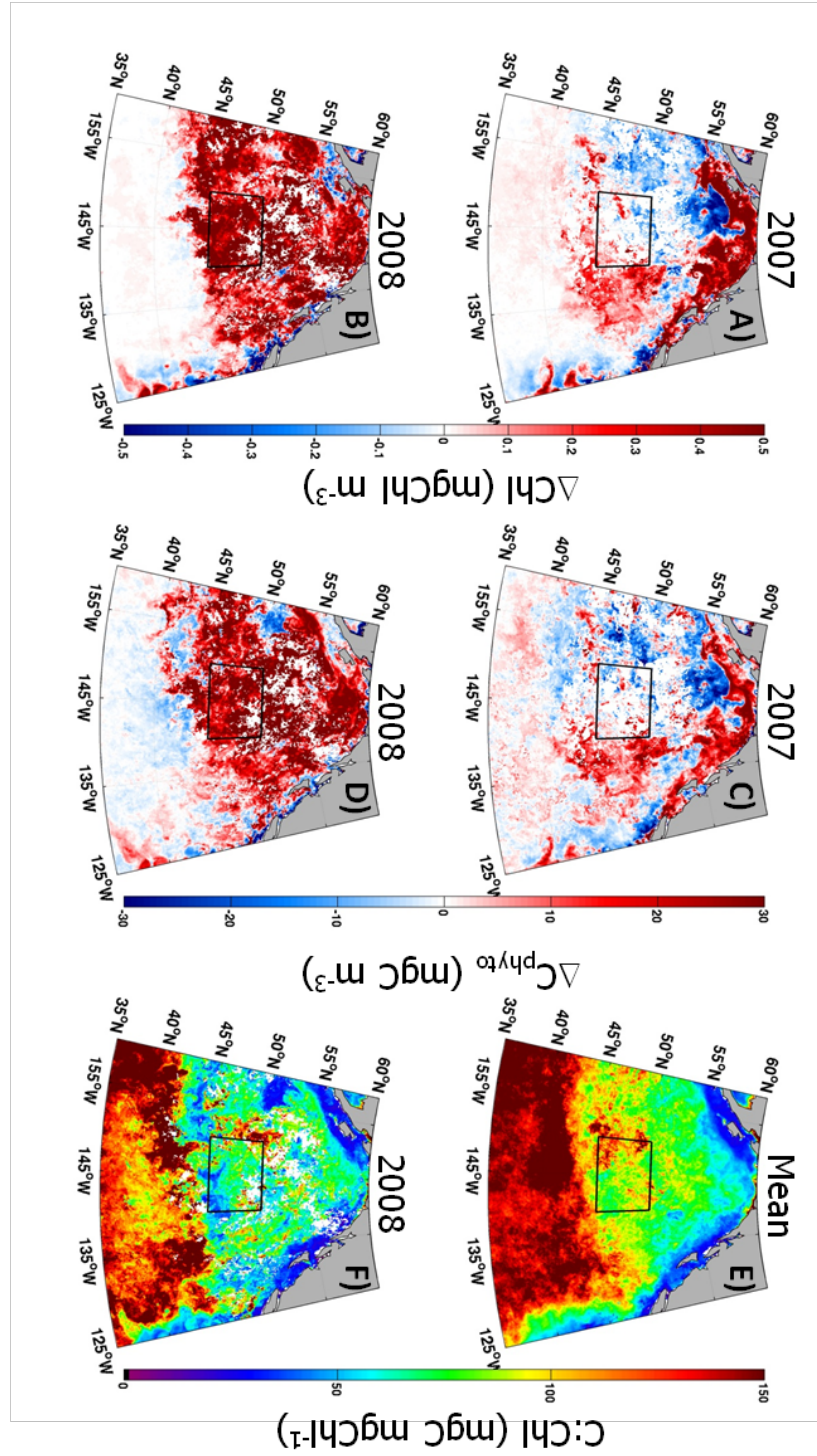


Figure S3. Satellite Chl, C_{phyto} and C:Chl in the NPac during August 2008. Anomalies in Chl and C_{phyto} (ΔChl and ΔC_{phyto} , respectively) were calculated relative to 10-year MODISA averages (2003-2012). A) ΔChl for August 2007, B) ΔChl for August 2008, C) ΔC_{phyto} for August 2007, D) ΔC_{phyto} for August 2008, E) Climatological mean C:Chl during August (2003-2012), F) C:Chl during August 2008. Outlined box is $5^\circ \times 10^\circ$ region used for analysis of annual cycles.

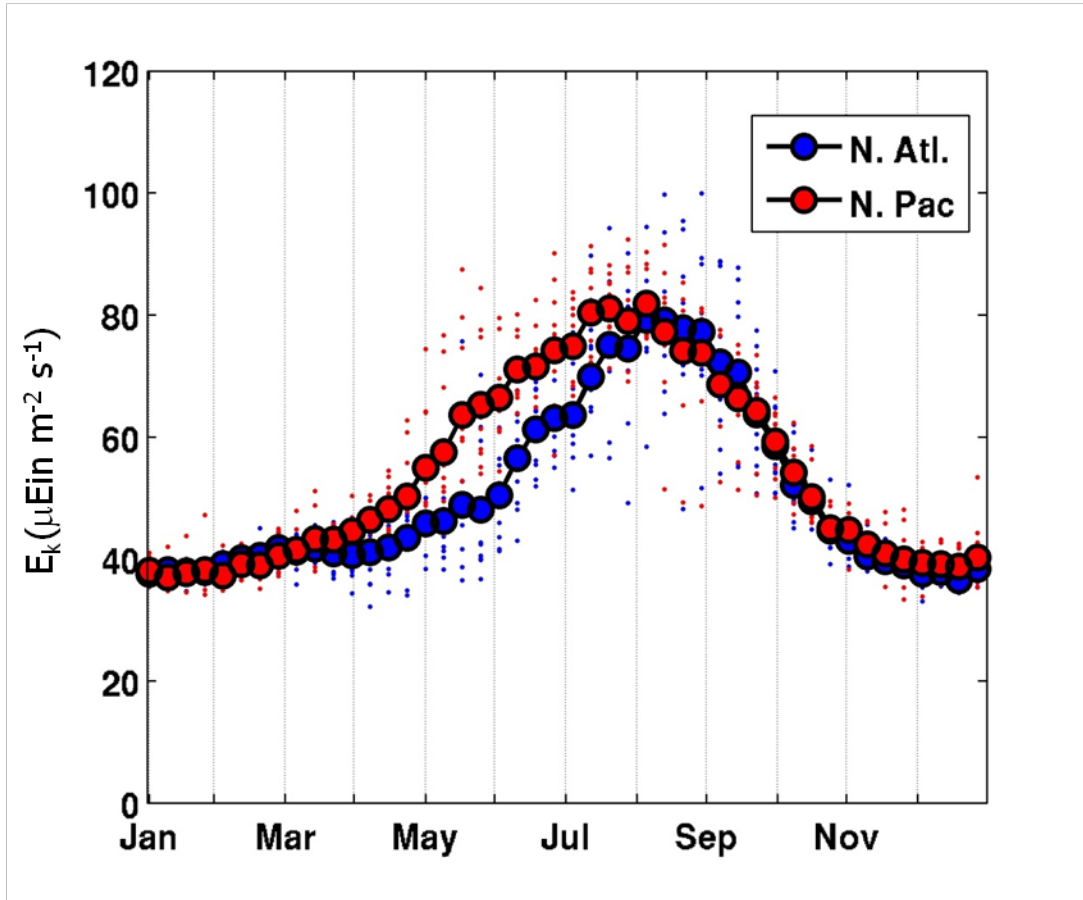


Figure S4. Annual cycle of light saturation parameter, E_k . E_k was calculated using estimates of PAR, MLD, and K_{PAR} (as shown in Figure 4 of the main manuscript) and the model of *Behrenfeld et al.* [2015].

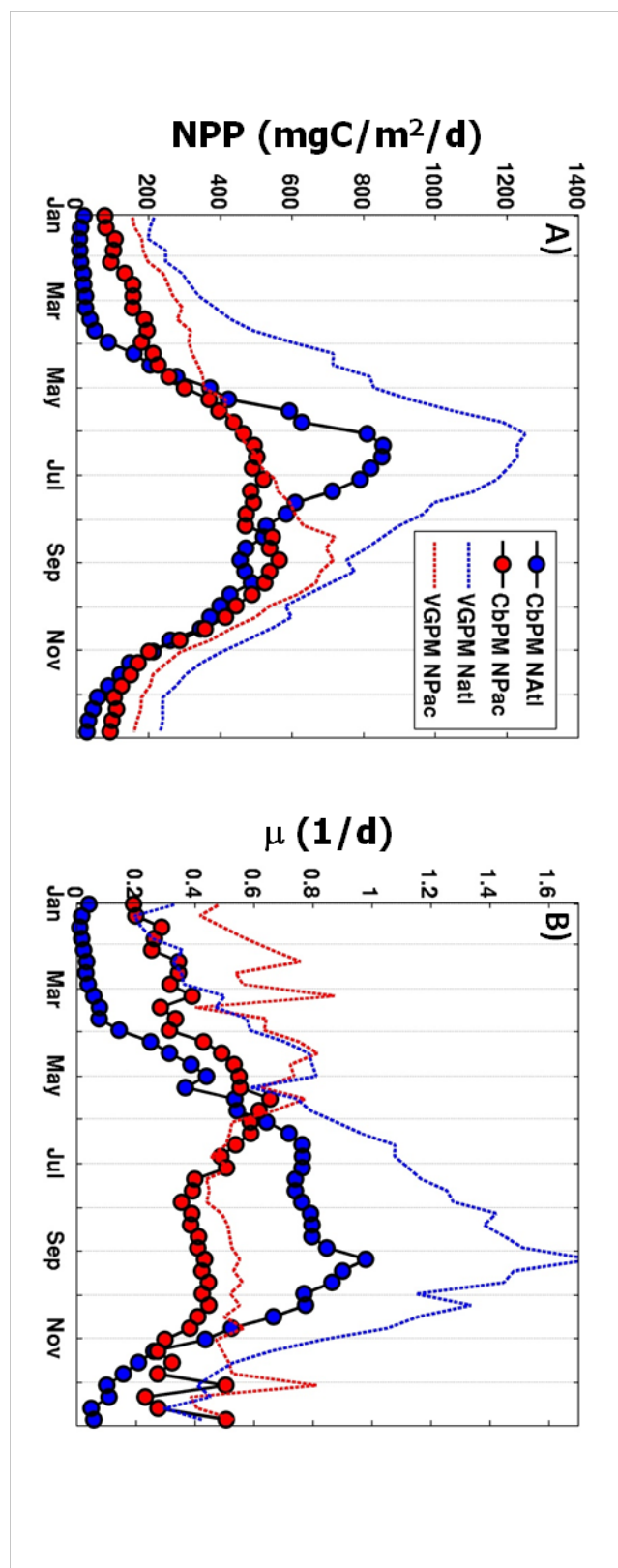


Figure S5. Annual cycles of net primary production (NPP) and phytoplankton growth rate (μ). A) NPP in the NATl and NPac from the Carbon-based Production Model (CbPM, filled circles) and Vertically Generalized Production Model (VGPM, dashed lines). B) μ estimated from the CbPM and VGPM, symbols and lines are the same as in panel A.