Arctic Ocean Primary Productivity

K. E. Frey[1], J. C. Comiso[2], L. W. Cooper[3], L. B. Eisner[4],
R. R. Gradinger[5], J. M. Grebmeier[3], J. -É. Tremblay[6]

[1]Graduate School of Geography, Clark University, Worcester, MA, USA
[2]Cryospheric Sciences Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD, USA
[3]Chesapeake Biological Laboratory, University of Maryland Center for Environmental Science, Solomons, MD, USA
[4]Alaska Fisheries Science Center, NOAA, Seattle, WA, USA
[5]UiT, The Arctic University of Norway, Tromsø, Norway
[6]Québec-Océan and Takuvik, Biology Department, Université Laval, Québec City, QC, Canada

Highlights

- Estimates of ocean primary productivity via satellite observations showed widespread positive (increasing) anomalies for 2017 (relative to the 2003-2016 mean) for all regions, with the most pronounced overall trends over the years 2003-2017 occurring in the Barents Sea and Eurasian Arctic regions.
- The regional distribution of positive (negative) anomalies in chlorophyll-*a* concentrations can often be associated with a relatively early (late) breakup of the sea ice cover.
- During May 2017, strong positive anomalies in chlorophyll-*a* concentrations occurred in the northwestern Bering Sea and in the southeastern Chukchi Sea off the coast of Point Hope, while widespread negative anomalies occurred in the Barents Sea. Negative anomalies for 2017 were also prevalent across broad areas of the Kara and Laptev seas, particularly during June, July, and August.
- Some of the most significant increases in chlorophyll-*a* concentrations over the years 2003-2017 have occurred during May in localized areas of the Labrador Sea and the Barents Sea.

Introduction

Autotrophic minute algae living in the sea ice (ice algae) and water column (phytoplankton) are the main primary producers in the Arctic Ocean. Through photosynthesis, they transform dissolved inorganic carbon dioxide into organic material. Consequently, primary production provides a key ecosystem service by providing energy to the entire food web in the oceans. The global oceans play a significant role in global carbon budgets via photosynthesis, contributing approximately half of Earth's net annual photosynthesis with ~10-15% of this production occurring on the continental shelves alone (Müller-Karger et al., 2005). Primary productivity is strongly dependent upon light availability and the presence of nutrients, and thus is highly seasonal in the Arctic region. In particular, the melting and retreat of sea ice during spring are strong drivers of primary production in the Arctic Ocean and its adjacent shelf seas due to enhanced light availability and stratification (Barber et al., 2015; Leu et al., 2015; Ardyna et al., 2017). Recent declines in Arctic sea ice extent (see the essay on *Sea Ice*) have contributed substantially to shifts in primary productivity throughout the Arctic Ocean. However, the response of primary production to sea ice loss has been both seasonally and spatially variable (e.g., Tremblay et al., 2015; Hill et al., 2017).

Here we present satellite-based estimates of algal chlorophyll-*a* (occurring in all species of phytoplankton), based on the color of the ocean, and subsequently provide calculated primary production estimates. These results are shown for ocean areas with less than 15% sea ice concentration and, therefore, do not include production by sea ice algae, open water from within the sea ice pack, or under-ice phytoplankton blooms.

Chlorophyll-*a*

Measurements of the algal pigment chlorophyll (e.g., chlorophyll-*a*) serve as a proxy for the amount of algal biomass present as well as overall plant health. Here we present the complete, updated MODIS-Aqua satellite chlorophyll-*a* record for the northern polar region for the years 2003-2017. A base period of 2003-2016 is chosen to calculate the 2017 anomalies to maximize the length of the short satellite-based time series.

The 2017 data show a distribution of both positive and negative anomalies in chlorophyll-*a* concentrations in a number of locations across the Arctic Ocean region, where patterns are spatially and temporally heterogeneous (**Fig. 1**). These patterns are often associated with the timing of sea ice breakup: positive anomalies tend to occur in regions where the breakup is relatively early, while negative anomalies tend to occur in regions where the breakup is delayed. The most notable positive anomaly in 2017 occurred during May, with high concentrations of chlorophyll-*a* (averaging over ~12 mg m^{-3} higher than the 2003-2016 mean) occurring across a relatively large (~500 x 350 km) region in the northwestern Bering Sea (**Figs. 1a** and **1e**). Strong positive anomalies in chlorophyll-*a* during May also occurred in the southeastern Chukchi Sea (off the coast of Point Hope, Alaska), where values averaged ~16 mg m^{-3} higher than the 2003-2016 mean across a ~100 x 150 km area (**Figs. 1a** and **1e**). One additional positive anomaly of note occurred in the northern Barents Sea (west of Novaya Zemlya) during June (**Fig. 1f**), where 2017 values were ~8 mg m^{-3} higher than the 2003-2016 mean. These positive anomalies are in contrast to widespread negative chlorophyll anomalies across the Barents Sea in May (**Fig. 1e**). Other widespread negative anomalies occurred across Baffin Bay during May (**Fig. 1e**) and the Kara and Laptev seas during all months (**Figs. 1e**, **1f**, **1g** and **1h**).

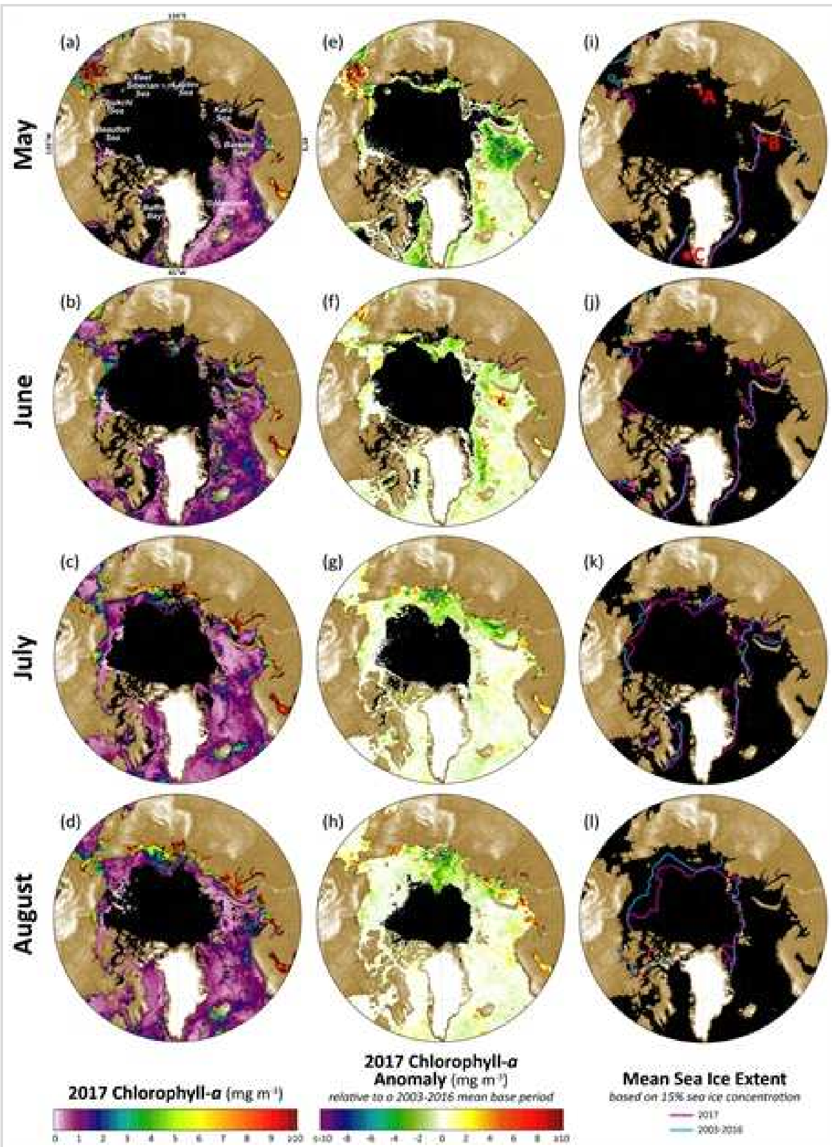

Fig. 1. Mean monthly chlorophyll-*a* concentrations during 2017 are shown for (a) May, (b) June, (c) July and (d) August. (e-h) Monthly anomalies of chlorophyll-*a* concentrations for 2017 (relative to a 2003-2016 mean base period). Black areas (a-h) denote a lack of data owing to either clouds or sea ice. (i-l) Sea ice extent (designated by a 15% sea ice concentration threshold) based on passive microwave satellite data (Cavalieri et al., 1996; Maslanik and Stroeve, 1999) for the 2003-2016 mean (cyan line) and 2017 (magenta line). The locations A, B and C in (i) indicate the locations for the time series shown in **Fig. 3**. Satellite-based chlorophyll-*a* data across the pan-Arctic region were derived using the MODIS-Aqua Reprocessing 2014.0, OC3 algorithm: http://oceancolor.gsfc.nasa.gov/.

The most significant rates of change in the 2003-2017 satellite record in May have occurred southwest of Greenland in the Labrador Sea and to the west of Novaya Zemlya in the Barents Sea (**Fig. 2a**) and reflect increasing chlorophyll-*a* concentrations. The increase in the Barents Sea has been associated with declines in sea ice (**Fig. 1i**) linked to the Atlantic Water inflow (e.g., Alexeev et al., 2013). Positive trends are less pronounced but become increasingly widespread here during June, July and August (**Fig. 2b**, **2c** and **2d**).

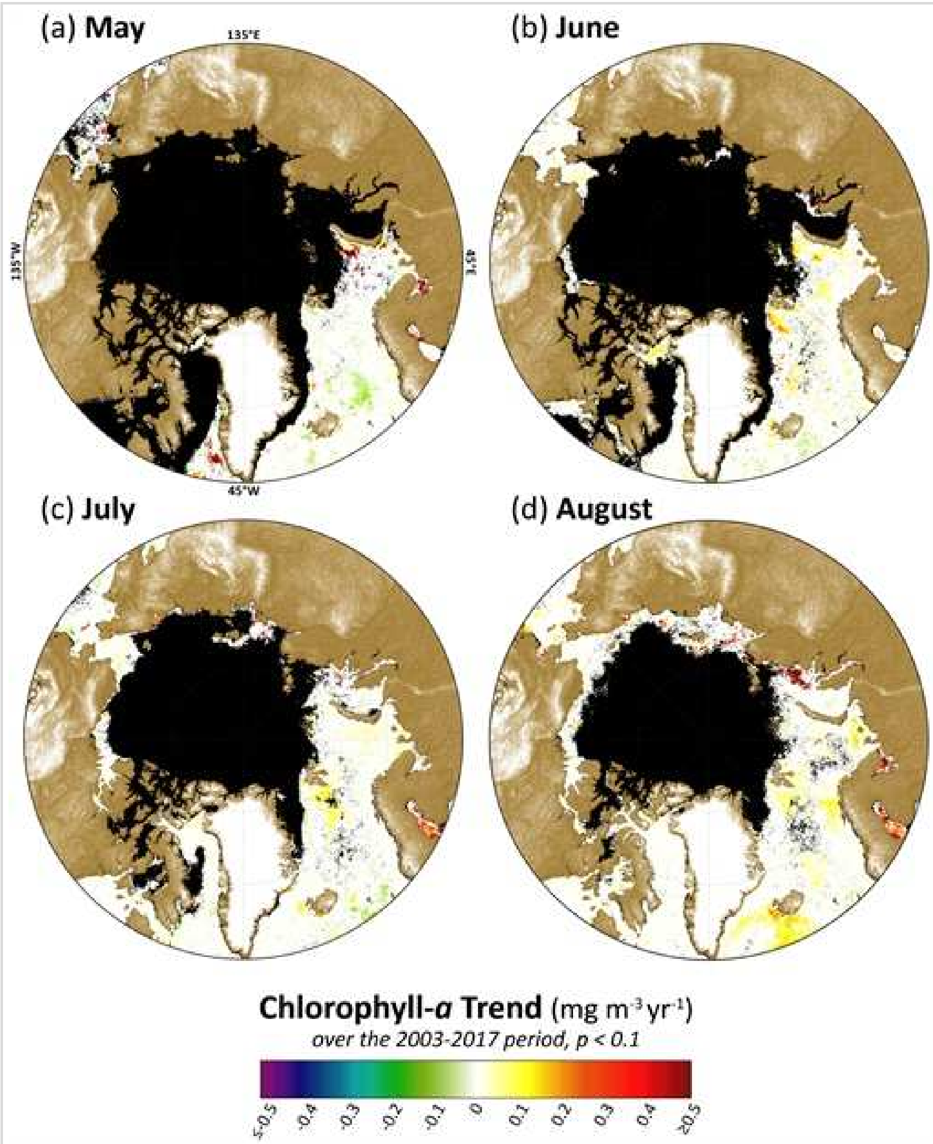

Fig. 2. Linear trends in satellite-based chlorophyll-*a* data across the pan-Arctic region, derived using the MODIS-Aqua Reprocessing 2014.0, OC3 algorithm: http://oceancolor.gsfc.nasa.gov/. Theil-Sen median trends (2003-2017) in chlorophyll-*a* concentrations for each of the four months are shown, highlighting only statistically significant trends ($p < 0.1$, using the Mann-Kendall test for trend). Black areas indicate where data were insufficient to calculate trends (owing to the presence of sea ice and/or cloud coverage) and white areas indicate no trend.

To illustrate the quantitative nature of these trends, three example "hotspot" regions (shown in **Fig. 1i**) with notably steep trends in chlorophyll-*a* for May, June, July and August 2003-2017 are shown in **Fig. 3**. Statistically significant trends ($p < 0.1$) occur in the region in the Laptev Sea (A), northwest of the New Siberian Islands, during June (**Fig. 3a**); during all months (May, June, July and August) in the region in the Barents Sea (B), west of Novaya Zemlya (**Fig. 3b**); and during May in the region in the Labrador Sea (C), southwest of Greenland (**Fig. 3c**). The largest blooms take place in May for the Barents and Labrador sea sites, but are delayed until August for the Laptev Sea site owing to the later breakup of sea ice across that region. The largest increases in chlorophyll-*a* concentrations have occurred during May in the

Labrador Sea (**Fig. 3c**) and the Barents Sea (**Fig. 3b**). In May 2017, there were relatively low chlorophyll-*a* concentrations at the Barents Sea site followed by relatively high concentrations in June (**Fig. 3b**). While many of these patterns are directly linked to sea ice variability (and therefore light availability), it is important to note that there are other dominant factors at play that add to the complexity of observed chlorophyll-*a* concentrations, such as the distribution and availability of nutrients.

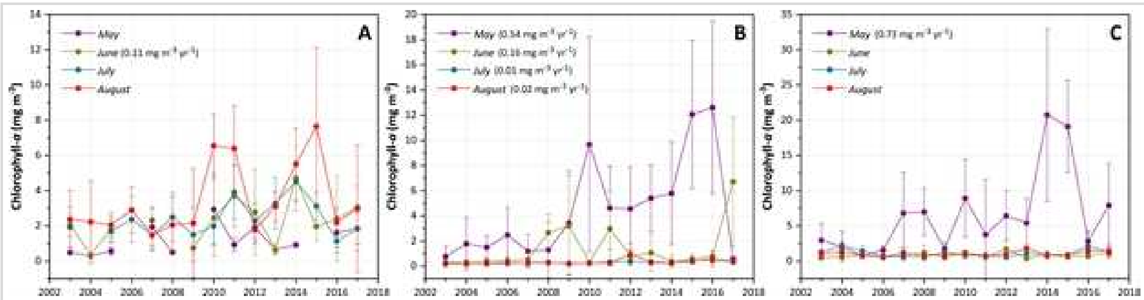

Fig. 3. Mean (±1 standard deviation) monthly chlorophyll-*a* concentrations (based on MODIS-Aqua satellite data) for May, June, July and August 2003-2017 for three example "hotspot" locations with notably steep trends in chlorophyll-*a*. Trends are shown for statistically significant ($p < 0.05$) time series only. The locations (shown in **Fig. 1i**) include (a) a ~22,500 km^2 region in the Laptev Sea northwest of the New Siberian Islands; (b) a ~25,400 km^2 region in the Barents Sea west of Novaya Zemlya; and (c) a 32,600 km^2 region in the Labrador Sea southwest of Greenland.

Primary Production

Chlorophyll-*a* concentrations give an estimate of the standing stock of algal biomass. Rates of primary production (i.e., the production of carbon via photosynthesis) give a slightly different perspective, and are calculated by combining chlorophyll-*a* concentrations with sea surface temperatures, incident solar irradiance, and mixed layer depths. Estimates of ocean primary productivity for nine regions (and the average of these nine regions) across the Arctic, relative to the 2003-2016 base period, indicate above average primary productivity for 2017 in all regions (**Fig. 4**, **Table 1**). Areas with the highest anomalies for 2017 include the Hudson Bay and Amerasian Arctic regions. In the longer term, positive trends in primary productivity occurred in all regions during the period 2003-2017 (**Fig. 4**, **Table 1**). Statistically significant trends occurred in the Eurasian Arctic, Barents Sea, Greenland Sea, Hudson Bay and North Atlantic, with the steepest trends found for the Barents Sea (15.9 g C/m^2/yr/dec) and the Eurasian Arctic (14.4 g C/m^2/yr/dec).

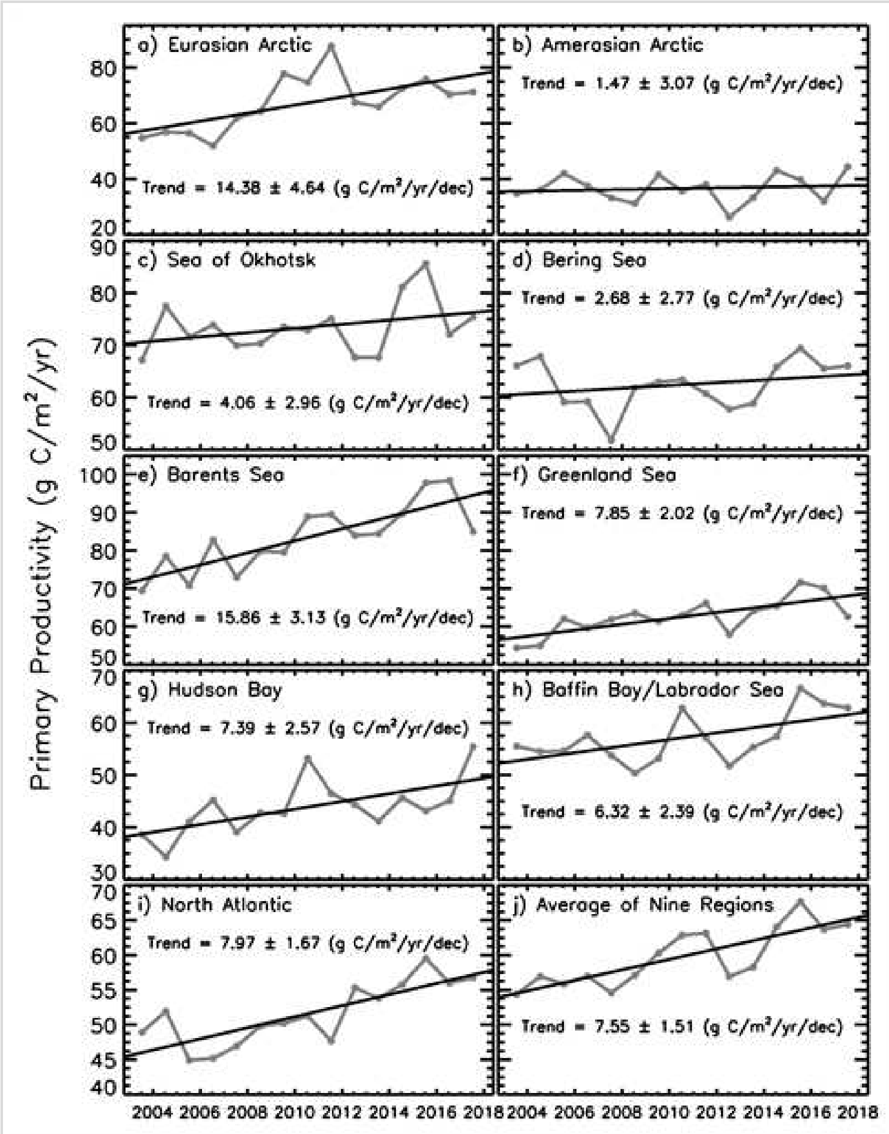

Fig. 4. Primary productivity (2003-2017, March-September only) in nine different regions of the Northern Hemisphere (for a definition of the regions see Comiso (2015)), as well as the average of these nine regions, derived using chlorophyll-*a* concentrations from MODIS-Aqua data, AVHRR sea surface temperature data, and additional parameters. Values are calculated based on the techniques described by Behrensfield and Falkowski (1997) and represent net primary productivity (NPP). Additional information regarding these data can be found in **Table 1**.

Table 1. Linear trends, statistical significance, percent change and primary productivity anomalies in 2017 (March-September) in the nine regions, and overall average, as shown in **Fig. 4**. Utilizing the Mann-Kendall test for trend, values in **bold** are significant at the 95% confidence level. The percent change is estimated from the linear regression of the 15-year time series.

Region	Trend, 2003-2017 (g C/m^2/yr/dec)	Mann-Kendall *p*-value	% Change	2017 Anomaly (g C/m^2/yr) *from a 2003-2016 base period*	2017 Anomaly (%) *from a 2003-2016 base period*
Eurasian Arctic	**14.38**	0.011	35.2	4.14	6.2
Amerasian Arctic	1.47	0.626	5.8	8.37	23.3
Sea of Okhotsk	4.06	0.282	8.1	2.14	2.9
Bering Sea	2.68	0.435	6.2	3.91	6.3
Barents Sea	**15.86**	0.000	30.7	1.65	2.0

Greenland Sea	**7.85**	0.003	19.2	0.02	0.0
Hudson Bay	**7.39**	0.011	26.7	12.39	28.8
Baffin Bay/Labrador Sea	6.32	0.093	16.8	6.13	10.8
North Atlantic	**7.97**	0.000	24.3	5.51	10.8
Average of Nine Regions	**7.55**	0.000	19.4	4.92	8.3

While similar trends have been reported previously for these regions using both SeaWiFS and MODIS data (Comiso, 2015), satellite evidence does suggest that recent increases in cloudiness have dampened the increases in production that would have otherwise occurred as a function of sea ice decline alone (Bélanger et al., 2013). Further challenges remain with linking primary productivity, as well depth-integrated chlorophyll biomass throughout the water column, to satellite-based surface chlorophyll-*a* values (Babin et al., 2015; Lee et al., 2015; Tremblay et al., 2015; Kahru, 2017). Satellite-based chlorophyll-*a* and primary productivity estimates continue to be confounded by issues such as river turbidity in coastal regions (e.g., Demidov et al., 2014; Chaves et al., 2015) and the presence of sea ice. Efforts to improve satellite retrieval algorithms based on in situ observations are thus critical to continue in all regions of the Arctic.

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