Arctic Ocean Primary Productivity: The Response of Marine Algae to Climate Warming and Sea Ice Decline

https://doi.org/10.25923/9ex0-t425

K. E. Frey[1], L. V. Stock[2], C. Garcia[3], L. W. Cooper[4], and J. M. Grebmeier[4]

[1]Graduate School of Geography, Clark University, Worcester, MA, USA
[2]Cryospheric Sciences Laboratory, Goddard Space Flight Center, NASA, Greenbelt, MD, USA
[3]Arctic Research Program, Global Ocean Monitoring and Observing Program, NOAA, Silver Spring, MD, USA
[4]Chesapeake Biological Laboratory, University of Maryland Center for Environmental Science, University of Maryland, Solomons, MD, USA

Headlines

- Satellite estimates of ocean primary productivity (i.e., the rate at which marine algae transform dissolved inorganic carbon into organic material) show lower values for 2024 (relative to the 2003-22 mean) for six of nine regions assessed across the Arctic.
- All regions, except for the Amerasian Arctic (namely the Chukchi Sea, Beaufort Sea, and Canadian Archipelago), continue to exhibit positive trends in ocean primary productivity during 2003-24, with the largest percent change in the Eurasian Arctic (+57.3%), Barents Sea (+20.5%), and Sea of Okhotsk (+13.5%).
- While lower-than-average values of annual ocean primary productivity were dominant across much of the Arctic for 2024, higher-than-average values were observed in eastern Hudson Bay, the Canadian Archipelago, and subareas of the Kara and Laptev Seas.

Introduction

Arctic marine primary productivity (the conversion of dissolved inorganic carbon into organic material by photosynthetic organisms) forms the foundation of the marine food web and plays a critical role in global carbon cycling. It is highly sensitive to changes in sea ice cover (see essay *Sea Ice*), ocean temperature (see essay *Sea Surface Temperature*), and nutrient availability, all of which are altered by ongoing climate change. Marine primary productivity in the Arctic varies significantly across different regions, influenced by local oceanographic conditions and the timing of sea ice retreat.

Recent in-situ observations reveal a complex picture: Although primary productivity has been boosted in many regions by thinner and more transparent sea ice, expanded ice-free areas, and enhanced nutrient upwelling (Fujiwara et al. 2018; Ardyna et al. 2020), the highest localized productivity is still associated with the retreating ice edge (Castagno et al. 2023; Amargant-Arumí et al. 2024) and lipid biomarker studies indicate that sea ice derived organic material is still critical on a year-round basis in Arctic ecosystems (Koch et al. 2023). Another complexity is that increased stratification and changing species compositions (Li et al. 2009) do not necessarily lead to long-term increases in primary production (Castro de la Guardia et al. 2023). The diverse sectors of the Arctic, from the Atlantic-influenced Barents

Sea to the Pacific-dominated Chukchi Sea, each respond uniquely to these changes, underscoring the need for region-specific analyses (e.g., Lalande et al. 2020).

Because of these complexities, synoptic observations using satellite-derived primary production data can be helpful in identifying localized productivity hotspots and phenological shifts that may not be apparent from traditional shipboard observations (Frey et al. 2023a). In this year's assessment, we continue to utilize Moderate Resolution Imaging Spectroradiometer (MODIS)-Aqua satellite data across the Arctic Ocean region, now spanning a 22-year record (2003-24). Monitoring these shifts remains vital given their profound implications for marine ecosystems, global climate feedback mechanisms, and marine resource management in a changing Arctic. The ongoing transformations in sea ice cover and ocean temperatures continue to reshape the patterns of primary productivity, highlighting the dynamic nature of the Arctic marine environment and the importance of sustained, accurate observations (Terhaar et al. 2021; Rantanen et al. 2022).

Chlorophyll-*a*

We present satellite-based estimates of algal chlorophyll-*a* (occurring in all species of phytoplankton), based on ocean color, and subsequently provide calculated primary production estimates (below). Observed patterns in chlorophyll-*a* (Fig. 1), which are spatially and temporally heterogeneous across the Arctic Ocean, are often associated with the timing of the seasonal break-up and retreat of the sea ice cover (Fig. 2) (see essay *Sea Ice*): high chlorophyll-*a* percentages (i.e., relative to the 2003-22 average) tend to occur in regions where the break-up is relatively early, while low percentages tend to occur in regions where the break-up is delayed. May 2024 (Fig. 1a) showed more geographically widespread higher-than-average chlorophyll-*a* concentrations than any other month of 2024, particularly in the Norwegian Sea, eastern Greenland Sea, Davis Strait, southeast Bering Sea, and eastern Hudson Bay (associated with early sea ice breakup in eastern Hudson Bay; Fig. 2a). During June 2024 (Fig. 1b), small areas of higher-than-average chlorophyll-*a* concentrations occurred in the Norwegian Sea, southeast Bering Sea, and northern Laptev Sea, but otherwise lower-than-average values were pervasive across the Arctic. During July 2024 (Fig. 1c), lower-than-average values were widespread across most of the Arctic, with areas of higher-than-average values in the Sea of Okhotsk, Bering Sea, East Siberian Sea, and southern Chukchi Sea. Lastly, during August 2024 (Fig. 1d), lower-than-average values were again observed across most of the Arctic, with noteworthy higher-than-average values clustered in the Bering Sea and southern Chukchi Sea.

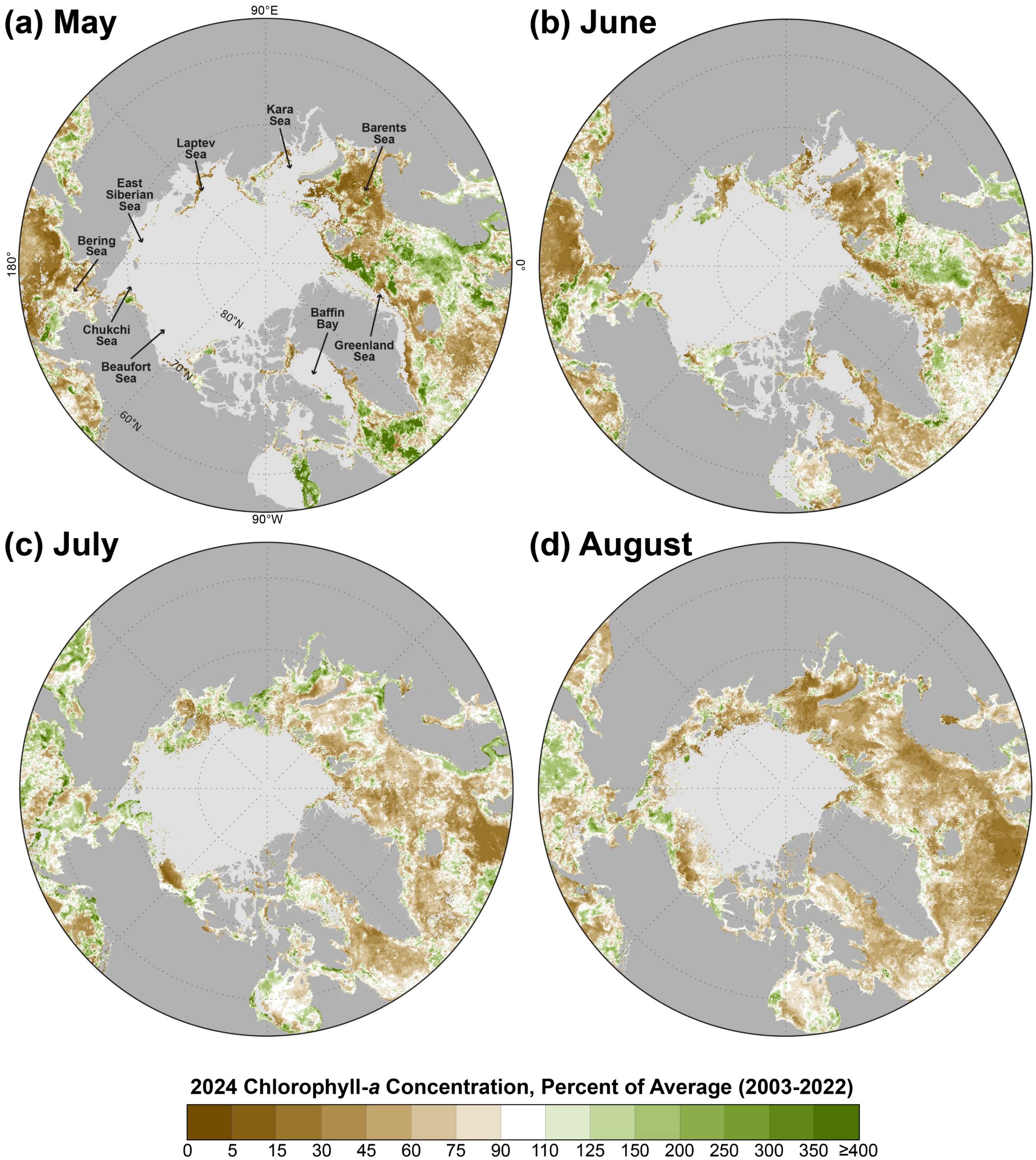

Fig. 1. Mean monthly chlorophyll-*a* concentrations during 2024, shown as a percent of the 2003-22 average for (a) May, (b) June, (c) July, and (d) August. August 2024 data were only available as Near Real Time (not final) data at the timing of this publication. The light gray regions represent areas where no data are available (owing to either the presence of sea ice or cloud cover). The color scale bar uses unequal intervals ranging from 5 to 50 percentage units, including the largest intervals for values greater than 125%. Data source: MODIS-Aqua Reprocessing 2022.0.1, chlor_a algorithm: http://oceancolor.gsfc.nasa.gov/.

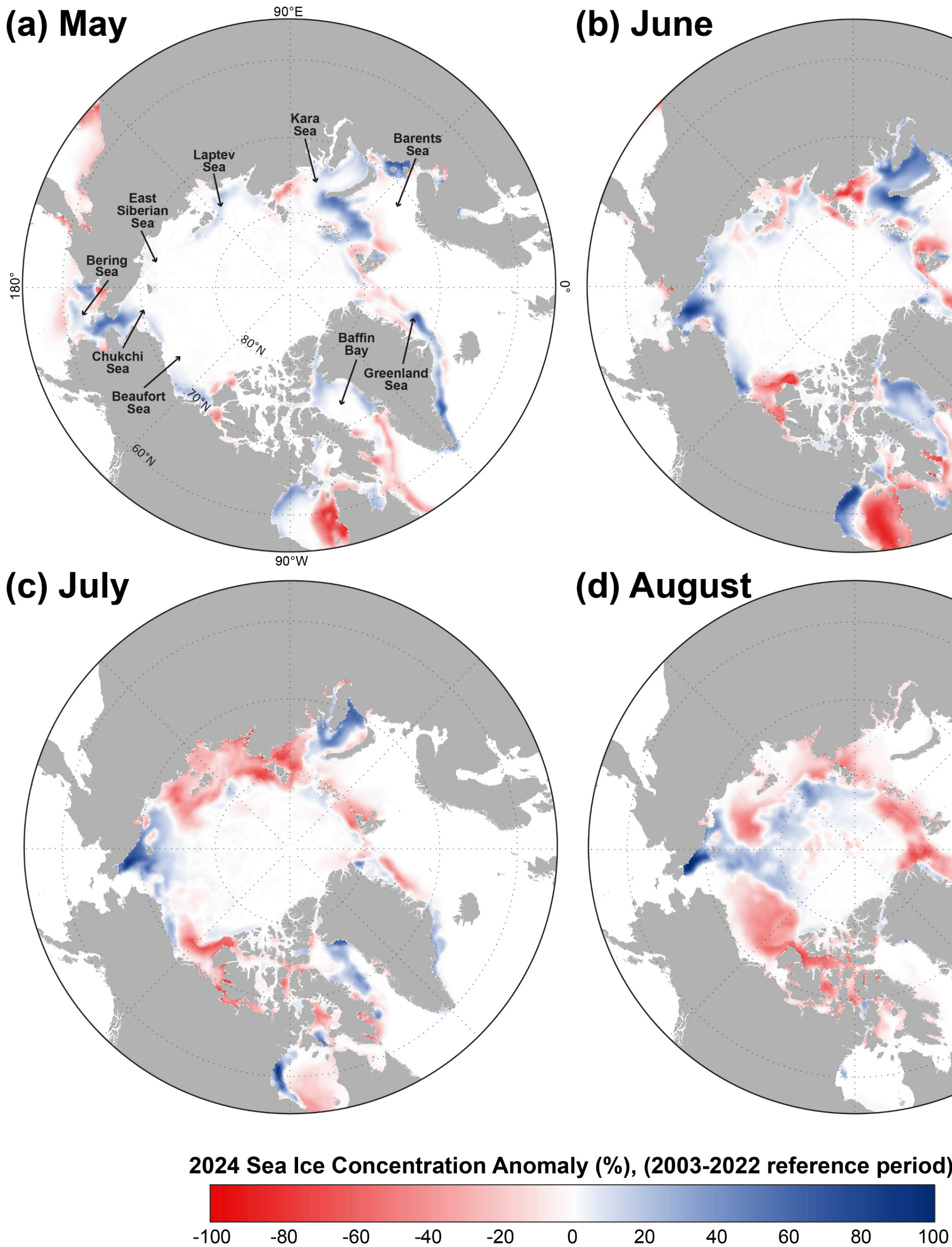

Fig. 2. Sea ice concentration anomalies (%) in 2024 (compared to a 2003-22 mean reference period) for (a) May, (b) June, (c) July, and (d) August. Data source: SSM/I and SSMIS passive microwave data, calculated using the Goddard Bootstrap (SB2) algorithm (Comiso et al. 2017).

Primary production

While chlorophyll-*a* concentrations give an estimate of the total standing stock of algal biomass, rates of primary production (i.e., the production of organic carbon via photosynthesis) provide a different perspective since not all algae in the water column are necessarily actively producing. The mean annual

(March through September) primary productivity across the Arctic shows important spatial patterns, most notably that productivity rates decrease northward as sea ice becomes more prevalent and nutrients become less available (Fig. 3a). Spatial trends in annual primary productivity (Fig. 3b) are a particularly useful tool for understanding hotspots of change. Statistically significant positive trends in primary productivity appear clustered in the Norwegian Sea, Barents Sea, Kara Sea, Laptev Sea, southeastern Chukchi Sea, and Canadian Archipelago (Fig. 3b). Positive trends adjacent to the Eurasian coastline may also be associated with variability in river-derived chromophoric (light absorbing) dissolved organic matter (CDOM) (e.g., Lewis and Arrigo 2020). There is almost no evidence of clustered significant negative trends in primary productivity across the Arctic (Fig. 3b). Investigations of 2024 annual primary productivity (Fig. 3c), as well as 2024 compared to the 2003-22 average (Fig. 3d), show higher-than-average annual productivity in eastern Hudson Bay, subareas of the Kara and Laptev Seas, and the Canadian Archipelago. Lower-than-average annual productivity occurred across much of the Arctic Ocean region for 2024, with the lowest values clustering in the East Siberian Sea, Chukchi Sea, and Beaufort Sea (Fig. 3d). Although sea ice cover was lower-than-average in large portions of the Beaufort Sea during July (Fig. 2c) and August (Fig. 2d), sea ice was either near-average or higher-than-average here during May (Fig. 2a) and June (Fig. 2b). For the East Siberian Sea and Chukchi Sea, sea ice was either near-average or higher-than-average during May through August (Fig. 2a-d). The overall higher sea ice cover or delayed sea ice breakup in these regions could have contributed to the widespread lower-than-average annual primary productivity rates also observed in these regions (Fig. 3d).

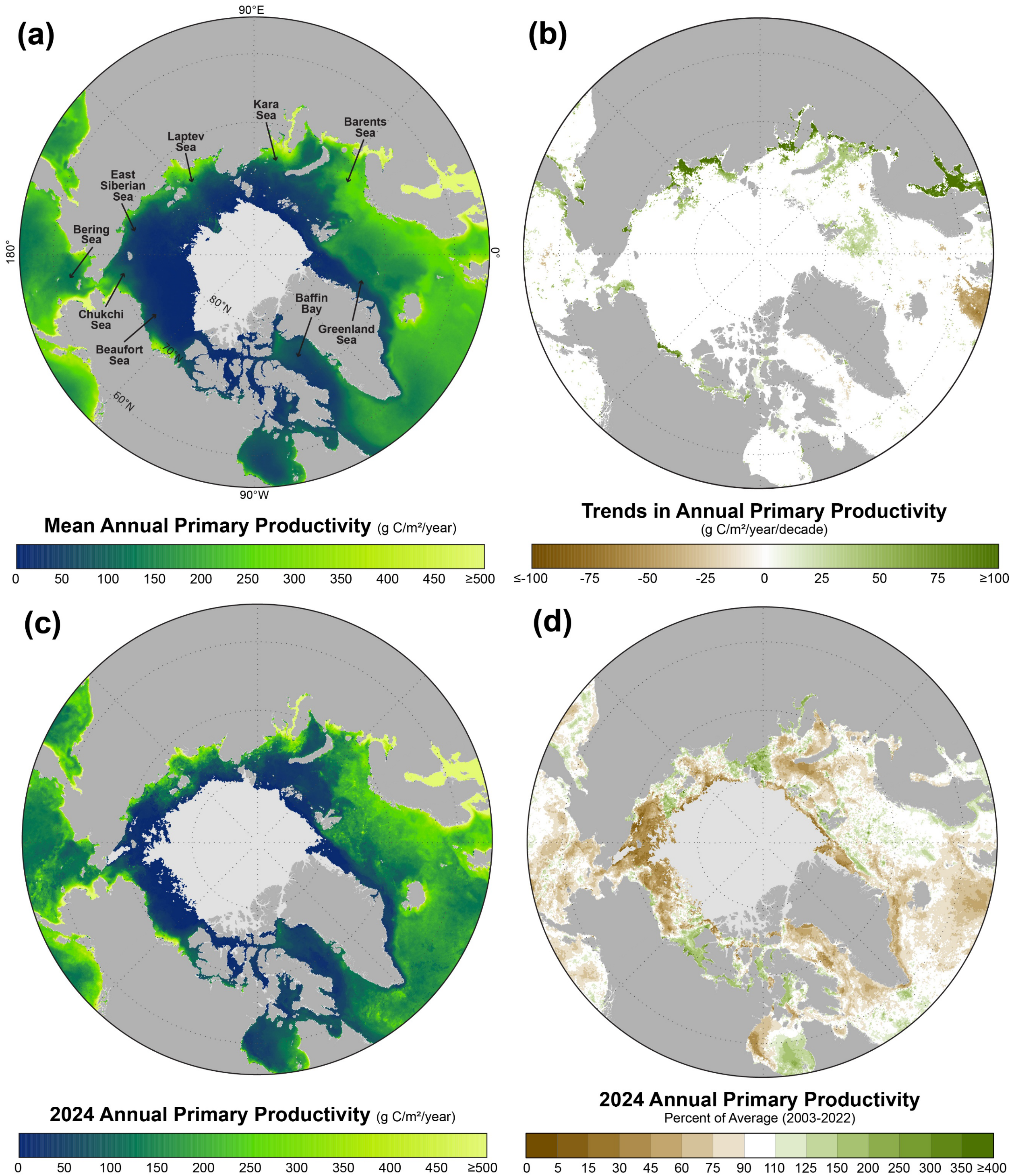

Fig. 3. For the pan-Arctic region: (a) mean annual (March-September only) primary productivity (2003-24); (b) trends in annual productivity (over 2003-24) where only those trends that are statistically significant (p<0.05) are shown; (c) annual primary productivity for 2024 only; and (d) 2024 annual primary productivity anomalies (shown as a percent of the 2003-22 average). In a, c, and d, light gray indicates no data owing to the presence of sea ice. Additional information regarding these data can be found in Table 1. August and September 2024 chlorophyll-*a* data (inputs into the primary productivity algorithm) were only available as Near Real Time (not final) data at the timing of this publication. See [*Methods and data*] section for details of how primary productivity was calculated.

Overall estimates of ocean primary productivity in 2024 for nine regions and across the Northern Hemisphere (relative to the 2003-22 reference period) were assessed (Fig. 4, Table 1). The Eurasian Arctic region includes the Kara, Laptev, and East Siberian Seas. The Amerasian Arctic region includes the Chukchi Sea, Beaufort Sea, and Canadian Archipelago. The North Atlantic is categorized as south of 60° N and east of 45° W, which excludes the Labrador and Greenland Seas. Our results show below-average primary productivity for 2024 in six of the nine regions assessed, while the Eurasian Arctic, Sea of Okhotsk, and Hudson Bay exhibited higher-than-average values (Fig. 4, Table 1). Positive trends in primary productivity continued in all regions (except for the Amerasian Arctic) during the 2003-24 period. Those trends that are statistically significant ($p<0.05$) occurred in the Eurasian Arctic (27.11 g C/m^2/yr/decade; a 57.3% increase), Barents Sea (15.07 g C/m^2/yr/decade; a 20.5% increase), and the Sea of Okhotsk (13.31 g C/m^2/yr/decade; a 13.5% increase). Annual net primary production was also calculated for the Arctic region, defined as 60-90° N (Fig. 5), which shows a trend over the 2003-24 time period of 14.7 Tg C/yr (Mann-Kendall significance $p<0.001$). The percent increase over the 22-year time series is estimated to be 19.2%. In summary, while observations of primary productivity show complex interannual and spatial patterns over the 2003-24 period, we continue to observe overall positive trends across most Arctic regions.

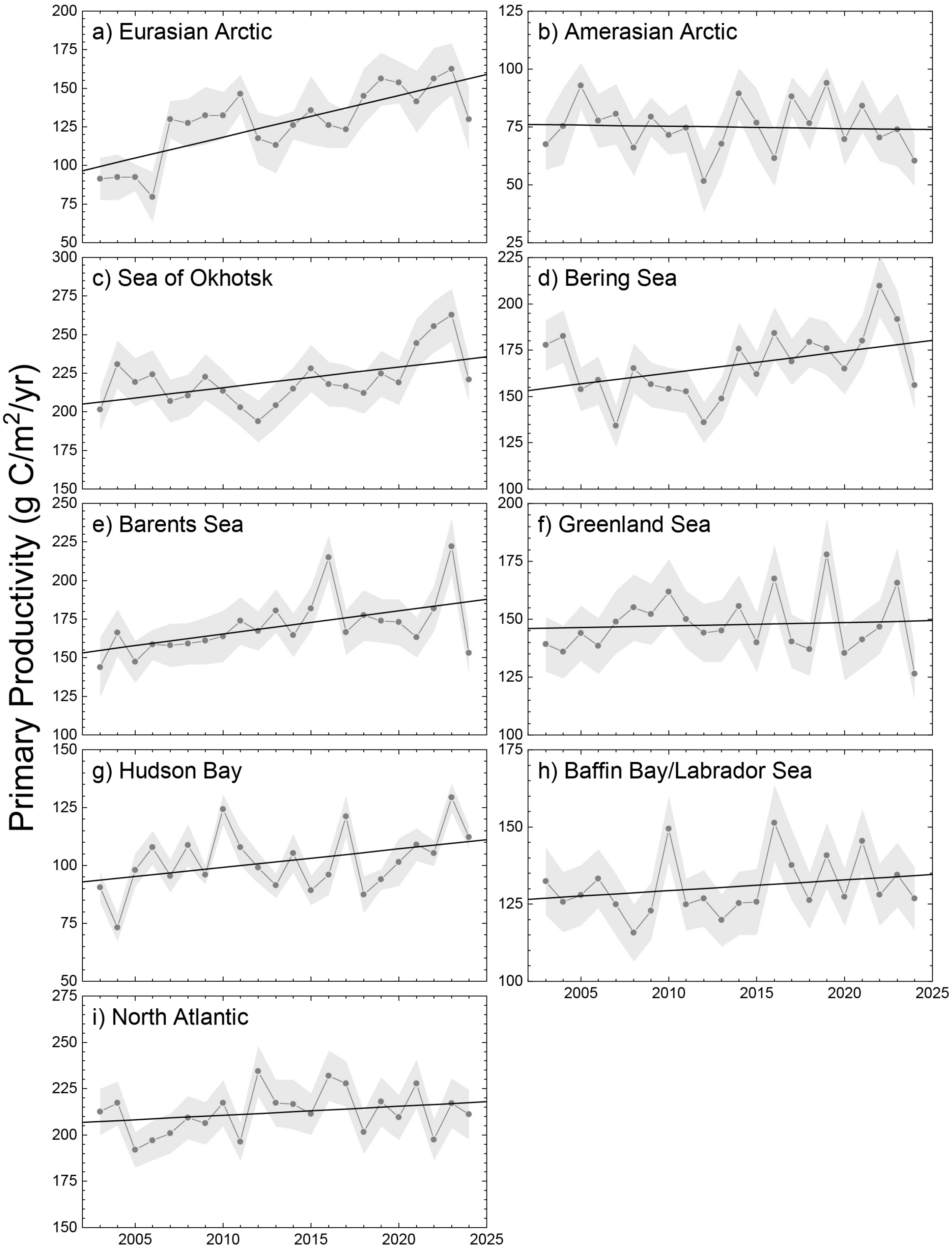

Fig. 4. Primary productivity (2003-24, March-September only) in nine different regions of the Northern Hemisphere (for a definition of the regions see Comiso 2015). The statistical significance of the trends (based on the Mann-Kendall test), *p*-values, and additional information regarding these data can be found in Table 1. August and September 2024 chlorophyll-*a* data (inputs into the primary productivity algorithm) were only available as Near Real Time (not final) data at the timing of this publication. See *Methods and data* section for primary productivity calculation details.

Table 1. Linear trends, statistical significance, and percent change in primary productivity (2003-24) and primary productivity anomalies for 2024 (March-September) in the nine regions as shown in Fig. 4. Values in bold are statistically significant (p<0.05) using the Mann-Kendall test for trend. The percent change was estimated from the linear regression of the 22-year time series.

Region	**2003-24** Trend (g C/m^2/yr/ decade)	**2003-24** Mann-Kendall p-value	**2003-24** % Change	**2024** Anomaly (g C/m^2/yr) from the 2003-22 reference period	**2024** Primary Productivity (% of the 2003-22 average)
Eurasian Arctic	**27.11**	<0.001	57.3	4.12	103.3
Amerasian Arctic	-0.99	0.697	-2.7	-15.36	79.7
Sea of Okhotsk	**13.31**	0.036	13.5	2.65	101.2
Bering Sea	11.75	0.081	16.0	-9.97	94.0
Barents Sea	**15.07**	0.002	20.5	-15.76	90.7
Greenland Sea	1.47	0.781	2.1	-21.40	85.5
Hudson Bay	7.94	0.116	17.8	12.20	112.2
Baffin Bay/Labrador Sea	3.52	0.161	5.8	-3.78	97.1
North Atlantic	4.87	0.289	4.9	-1.09	99.5

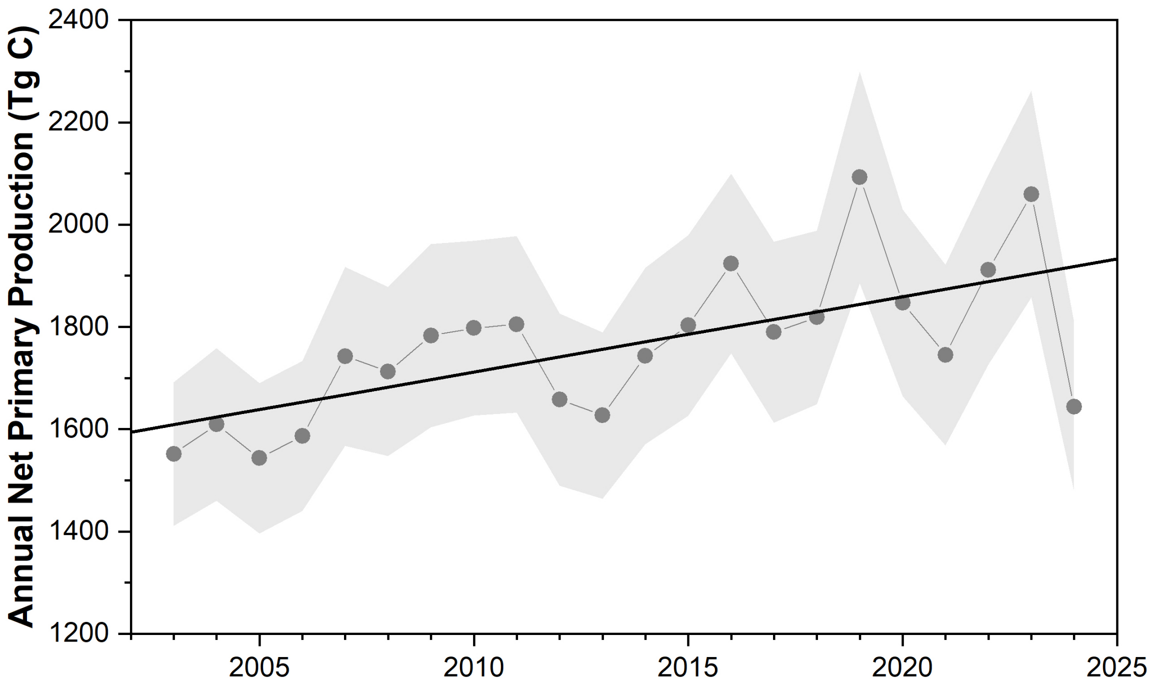

Fig. 5. Annual net primary production (2003-24, March-September only) for the Arctic region defined as 60-90° N. The trend over the 2003-24 time period is 14.7 Tg C/yr (Mann-Kendall significance $p<0.001$). The percent change estimated from the linear regression over the 22-year time series is 19.2%. August and September 2024 chlorophyll-*a* data (inputs into the primary productivity algorithm) were only available as Near Real Time (not final) data at the timing of this publication. See *Methods and data* section for primary productivity calculation details.

Methods and data

Measurements of the algal pigment chlorophyll (specifically, chlorophyll-*a*) serve as a proxy for algal biomass present in the ocean as well as overall plant health. The complete, updated MODIS-Aqua satellite record of chlorophyll-*a* concentrations within northern polar waters for the years 2003-24 serves as a time-series against which individual years can be compared. Satellite-based chlorophyll-*a* data across the pan-Arctic region were derived using the MODIS-Aqua Reprocessing 2022.0.1 (July 2024), chlor_a algorithm: http://oceancolor.gsfc.nasa.gov/. For this report, we show mean monthly chlorophyll-*a* concentrations calculated as a percentage of the 2003-22 average. This is the first time the same reference period (2003-22) has been utilized in two consecutive Arctic Ocean Primary Productivity Arctic Report Card essays (i.e., Frey et al. 2023b; *this essay*) now that the MODIS-Aqua satellite record has accrued at least 20 years of data. Satellite-based sea ice concentrations were derived from the Special Sensor Microwave/Imager (SSM/I) and Special Sensor Microwave Imager/Sounder (SSMIS) passive microwave instruments, calculated using the Goddard Bootstrap (SB2) algorithm (Comiso et al. 2017). Monthly sea ice concentration anomalies were additionally calculated for 2024 (compared to the 2003-22 average) to streamline comparisons with the variability in monthly chlorophyll-*a* satellite data. Primary productivity data were derived using chlorophyll-*a* concentrations from MODIS-Aqua data (Reprocessing 2022.0.1, chlor_a algorithm), the NOAA 1/4° daily Optimum Interpolation Sea Surface Temperature dataset (or daily OISST) that uses satellite sea surface temperatures from AVHRR, incident solar irradiance, mixed layer depths, and additional parameters. Primary productivity values were calculated based on the Vertically Generalized Production Model (VGPM) algorithm described by Behrenfeld and Falkowski (1997) as applied by Frey et al. (2023a). Chlorophyll-*a* and primary productivity data only incorporate pixels where sea ice is less than 10%, which is a compromise between potential pixel contamination with sea ice and an attempt to incorporate open water near the ice edge that typically exhibits high rates of primary production. We define annual productivity as productivity over the March-September time period. The 2024 annual primary productivity percent of average (compared to 2003-22) was calculated the same way as for chlorophyll-*a*, as described above. Lastly, spatial trends of primary productivity (Fig. 3b) were calculated using a Theil-Sen median trend estimator, and regional (and total Arctic) linear trends/percent change (Table 1, Figs. 4 and 5) were calculated through ordinary least squares regression. The statistical significance of all trends ($p<0.05$) was determined using the Mann-Kendall trend test. The MODIS-Aqua Reprocessing 2022.0.1 (https://oceancolor.gsfc.nasa.gov/data/reprocessing/r2022.0.1/aqua/) that took place in July 2024 includes revised data from 2021-present in response to satellite orbital shifts and resulting declines in data accuracy. As such, values and trends shown in our time series analyses this year (e.g., Table 1, Figs. 1, 3, 4, and 5) are updated from previous Arctic Report Card essays based on these newly revised data for 2021 onwards.

Importantly, the chlorophyll-*a* and primary productivity data are shown for ocean areas with less than 10% sea ice concentration and, therefore, do not include production by sea ice algae or under-ice phytoplankton blooms, which can be significant (Ardyna et al. 2013). Furthermore, it is known that satellite observations can underestimate production under stratified conditions when a deep chlorophyll maximum is present. The variable distribution of sediments and CDOM (owing to riverine delivery, coastal erosion, and sea ice dynamics) can also affect the accuracy of satellite-based estimations of chlorophyll-*a* and primary productivity in Arctic waters (Lewis and Arrigo 2020). As such, in-situ observations continue to provide important overall context for changes to and drivers of primary productivity across Arctic marine ecosystems.

Acknowledgments

K. Frey acknowledges financial support from the National Science Foundation (NSF) Arctic Observing Network (AON) Program (Grant 1917434). Support for J. Grebmeier and L. Cooper was provided through NSF AON (Grant 1917469) and the NOAA Global Ocean Monitoring and Observing, Arctic Research Program (CINAR 22309.07_UMCES_Grebmeier).

References

Amargant-Arumí, M., and Coauthors, 2024: Interannual differences in sea ice regime in the north-western Barents Sea cause major changes in summer pelagic production and export mechanisms. *Prog. Oceanogr.*, **220**, 103178, https://doi.org/10.1016/j.pocean.2023.103178.

Ardyna, M., M. Babin, M. Gosselin, E. Devred, S. Bélanger, A. Matsuoka, and J. -É. Tremblay, 2013: Parameterization of vertical chlorophyll *a* in the Arctic Ocean: impact of the subsurface chlorophyll maximum on regional, seasonal, and annual primary production estimates. *Biogeosciences*, **10**(6), 4383-4404, https://doi.org/10.5194/bg-10-4383-2013.

Ardyna, M., and Coauthors, 2020: Under-ice phytoplankton blooms: Shedding light on the "invisible" part of Arctic primary production. *Front. Mar. Sci.*, **7**, 608032, https://doi.org/10.3389/fmars.2020.608032.

Behrenfeld, M. J., and P. G. Falkowski, 1997: Photosynthetic rates derived from satellite-based chlorophyll concentration. *Limnol. Oceanogr.*, **42**(1), 1-20, https://doi.org/10.4319/lo.1997.42.1.0001.

Castagno, A. P., T. J. W. Wagner, M. R. Cape, C. W. Lester, E. Bailey, C. Alves-de-Souza, R.A. York, and A. H. Fleming, 2023: Increased sea ice melt as a driver of enhanced Arctic phytoplankton blooming. *Glob. Change Biol.*, **29**(17), 5087-5098, https://doi.org/10.1111/gcb.16815.

Castro de la Guardia, L., and Coauthors, 2023: Assessing net primary production in the northwestern Barents Sea using in situ, remote sensing and modelling approaches. *Prog. Oceanogr.*, **219**, 103160, https://doi.org/10.1016/j.pocean.2023.103160.

Comiso, J. C., 2015: Variability and trends of the global sea ice cover and sea level: Effects on physicochemical parameters. *Climate Change and Marine and Freshwater Toxins*, L. M. Botana, M. C. Lauzao, and N. Vilarino, Eds., De Gruyter, Berlin, Germany, https://doi.org/10.1515/9783110333596-003.

Comiso, J. C., W. N. Meier, and R. Gersten, 2017: Variability and trends in the Arctic Sea ice cover: Results from different techniques. *J. Geophys. Res.-Oceans*, **122**, 6883-6900, https://doi.org/10.1002/2017JC012768.

Frey, K. E., J. C. Comiso, L. V. Stock, L. N. C. Young, L. W. Cooper, and J. M. Grebmeier, 2023a: A comprehensive satellite-based assessment across the Pacific Arctic Distributed Biological Observatory shows widespread late-season sea surface warming and sea ice declines with significant influences on primary productivity. *PLoS ONE*, **18**(7), e0287960, https://doi.org/10.1371/journal.pone.0287960.

Frey, K. E., J. C. Comiso, L. W. Cooper, C. Garcia, J. M. Grebmeier, and L. V. Stock, 2023b: Arctic ocean primary productivity: The response of marine algae to climate warming and sea ice decline. *Arctic Report Card 2023*, R. L. Thoman, T. A. Moon, and M. L. Druckenmiller, Eds., https://doi.org/10.25923/nb05-8w13.

Fujiwara, A., and Coauthors, 2018: Changes in phytoplankton community structure during wind-induced fall bloom on the central Chukchi shelf. *Polar Biol.*, **41**, 1279-1295, https://doi.org/10.1007/s00300-018-2284-7.

Koch, C. W., and Coauthors, 2023: Year-round utilization of sea ice-associated carbon in Arctic ecosystems. *Nat. Commun.*, **14**, 1964, https://doi.org/10.1038/s41467-023-37612-8.

Lalande, C., J. M. Grebmeier, R. R. Hopcroft, and S. L. Danielson, 2020: Annual cycle of export fluxes of biogenic matter near Hanna Shoal in the northeast Chukchi Sea. *Deep-Sea Res. Pt. II*, **177**, 104730, https://doi.org/10.1016/j.dsr2.2020.104730.

Lewis, K. M., and K. R. Arrigo, 2020: Ocean color algorithms for estimating chlorophyll *a*, CDOM absorption, and particle backscattering in the Arctic Ocean. *J. Geophys. Res.- Ocean*s, **125**, e2019JC015706, https://doi.org/10.1029/2019JC015706.

Li, W. K., F. A. McLaughlin, C. Lovejoy, and E. C. Carmack, 2009: Smallest algae thrive as the Arctic Ocean freshens. *Science*, **326**, 539-539, https://doi.org/10.1126/science.1179798.

Rantanen, M., A. Y. Karpechko, A. Lipponen, K. Nordling, O. Hyvärinen, K. Ruosteenoja, T. Vihma, and A. Laaksonen, 2022: The Arctic has warmed nearly four times faster than the globe since 1979. *Commun. Earth Environ.*, **3**, 168, https://doi.org/10.1038/s43247-022-00498-3.

Terhaar, J., R. Lauerwald, P. Regnier, N. Gruber, and L. Bopp, 2021: Around one third of current Arctic Ocean primary production sustained by rivers and coastal erosion. *Nat. Commun.*, **12**, 169, https://doi.org/10.1038/s41467-020-20470-z.

November 15, 2024