

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

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Headlines

- Satellite estimates of ocean primary productivity (i.e., the rate at which marine algae transform dissolved inorganic carbon into organic material) show higher values for 2025 (relative to the 2003-22 mean) for eight of nine regions assessed across the Arctic.
- All regions, except for the Amerasian Arctic (the combined Chukchi Sea, Beaufort Sea, and Canadian Archipelago), continue to exhibit positive trends in ocean primary productivity during 2003-25, with the largest percent changes in the Eurasian Arctic (+80.2%), Barents Sea (+33.8%), and Hudson Bay (+27.1%).
- While higher primary productivity may enhance carbon availability to food webs in some cases, important negative impacts to ecosystem health also result from trophic mismatches that stymie the movement of carbon through the food chain as well as the increasing prevalence of harmful algal blooms.

Introduction

Arctic marine primary productivity, the fundamental process by which marine algae convert dissolved inorganic carbon into organic material through photosynthesis, forms the foundation of the marine food web and plays a critical role in global carbon cycling. This biological engine 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 being altered by ongoing Arctic warming. As the Arctic is warming at nearly four times the global average rate (Rantanen et al. 2022), marine primary productivity continues to exhibit complex regional and temporal responses across the Arctic Ocean.

Recent in-situ observations reveal multifaceted primary productivity changes. While many regions show increased productivity owing to thinner and more light-transmissive sea ice, expanded ice-free areas, and enhanced nutrient upwelling (Ardyna et al. 2020), the highest localized productivity remains associated with the retreating ice edge (Castagno et al. 2023). Organic matter from ice-associated algae continues to play a critical year-round role in Arctic ecosystems (Koch et al. 2023). However, increased stratification and shifts from larger diatoms to smaller flagellates may inhibit long-term production or

efficient energy transfer (Li et al. 2009). The diverse sectors of the Arctic Ocean also respond uniquely to environmental changes, from the Atlantic-influenced Eurasian Basin (see essay [Atlantification of the Arctic Ocean](#)) experiencing increased Atlantic water inflow and warming, to the Pacific-dominated Chukchi Sea receiving variable nutrient inputs through Bering Strait. These regional variations are further complicated by increasing riverine discharge delivering both nutrients and chromophoric (i.e., colored) dissolved organic matter (CDOM), which can either enhance or inhibit productivity depending on local conditions (Lewis and Arrigo 2020; Mathew et al. 2025).

Increasing primary productivity in Arctic regions has both ecological and societal relevance as an indicator of ecosystem health. Higher productivity may enhance carbon availability to food webs, potentially benefiting zooplankton and benthic populations. However, concurrent trends of reduced ice cover, warming seawater, and enhanced stratification can cause shifts in the timing and species composition of phytoplankton blooms, which can negatively impact ecosystem dynamics by causing trophic mismatches (and therefore reduced utilization of carbon through the food chain). Furthermore, sea-ice obligate species at higher trophic levels (e.g., Arctic cod, Pacific walruses, and several species of ice seals) can be severely impacted by declining sea ice regardless of food availability. Adding to these challenges, recent warming in the Pacific Arctic has increased the occurrence of algal species that synthesize toxins that can be transmitted through the food web and potentially affect the health of subsistence-based coastal communities (Anderson et al. 2022). Observing and understanding changes in regional primary productivity across the Arctic are essential for predicting ecosystem trajectories, managing marine resources, and understanding food security issues across human societies (Huntington et al. 2022).

Satellite remote sensing provides critical synoptic observations for tracking productivity patterns across the vast Arctic Ocean. The Moderate Resolution Imaging Spectroradiometer (MODIS)-Aqua satellite record, now spanning over two decades (2003-25), enables detection of localized productivity hotspots, phenological shifts, and long-term trends that otherwise would be impossible to capture through shipboard observations alone (Frey et al. 2023a). In this year's assessment, we utilized the extended MODIS-Aqua record to present satellite-derived estimates of Arctic Ocean primary productivity for 2025, examining regional variations and contextualizing current conditions over the 23-year observational record.

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 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 2025 (Fig. 1a) showed clear higher-than-average chlorophyll-*a* concentrations along the sea ice edge in the Greenland Sea, with distributions of lower-than-average values in the Barents and Bering Seas. During June 2025 (Fig. 1b), higher-than-average chlorophyll-*a* concentrations continued in the Greenland Sea and emerged in portions of the Barents, Kara, and Bering Seas. During July 2025 (Fig. 1c), higher-than-average values were apparent in the western Barents, Kara, Laptev, and Bering Seas, with lower-than-average values developing in the Greenland and central Barents Seas. During August 2025 (Fig. 1d), spatial patterns remained heterogeneous showing higher-than-average values in the Kara and western Barents Seas, with noteworthy lower-than-average values

clustered in the eastern Barents, Laptev, East Siberian, Chukchi, and Beaufort Seas. Examples of clear connections between chlorophyll-*a* and sea ice include: (1) a likely strong sea ice edge bloom in the eastern Greenland Sea during May (Fig. 1a) associated with higher-than-average sea ice concentrations adjacent to the west (Fig. 2a); and (2) high chlorophyll-*a* concentrations in the Kara Sea during June (Fig. 1b) geographically coincident with lower-than-average sea ice cover across the region (Fig. 2b).

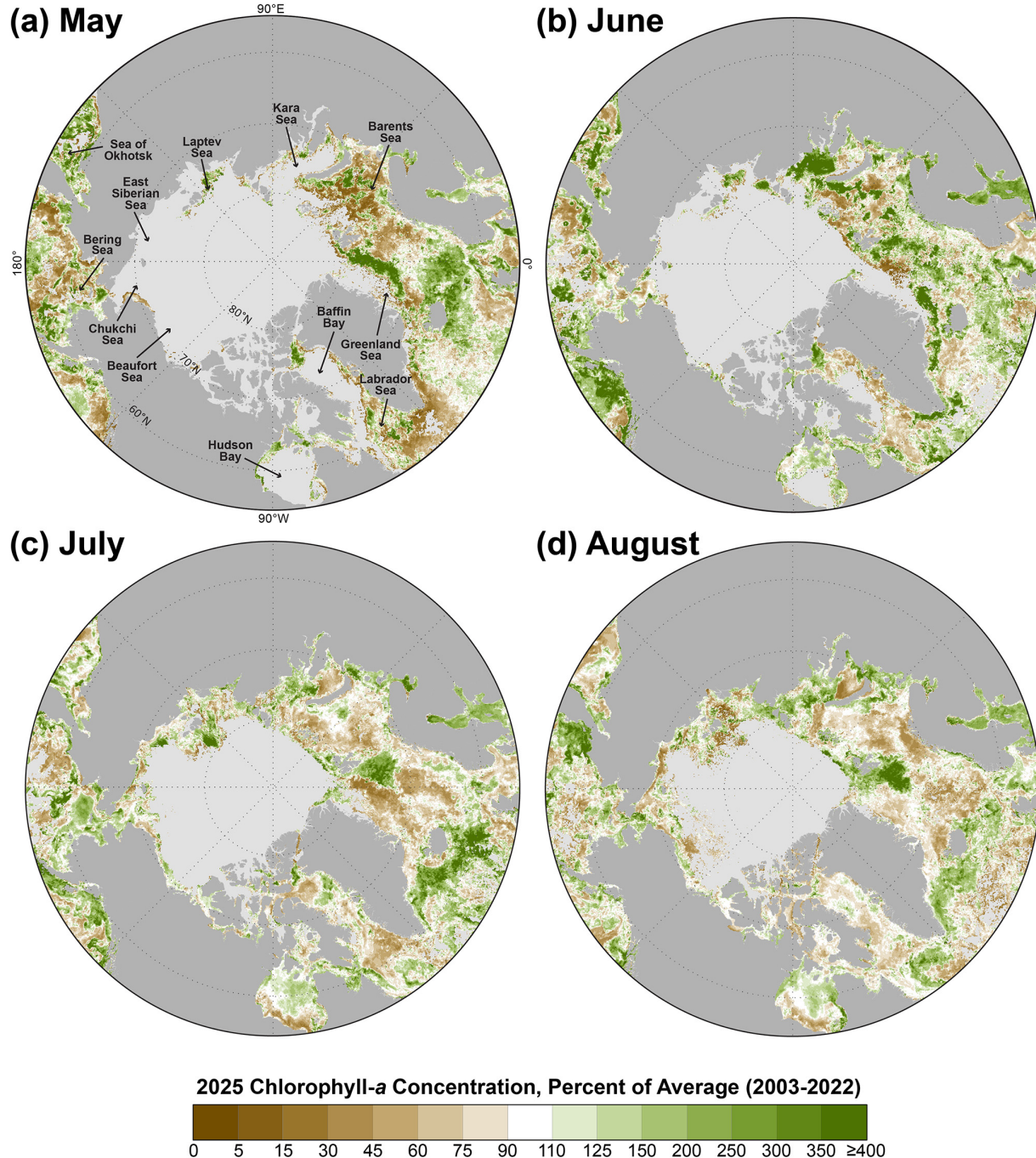


Fig. 1. Mean monthly chlorophyll-*a* concentrations during 2025, shown as a percent of the 2003-22 average for (a) May, (b) June, (c) July, and (d) August. The light gray regions represent areas where no data are available (owing to either the presence of sea ice or cloud cover). The color scale bar uses unequal intervals ranging from 5 to 50 percentage units, where the largest intervals are used for values greater than 125%. Data source: MODIS-Aqua Reprocessing 2022.0.2, chlor_ *a* algorithm: <https://oceancolor.gsfc.nasa.gov/>.

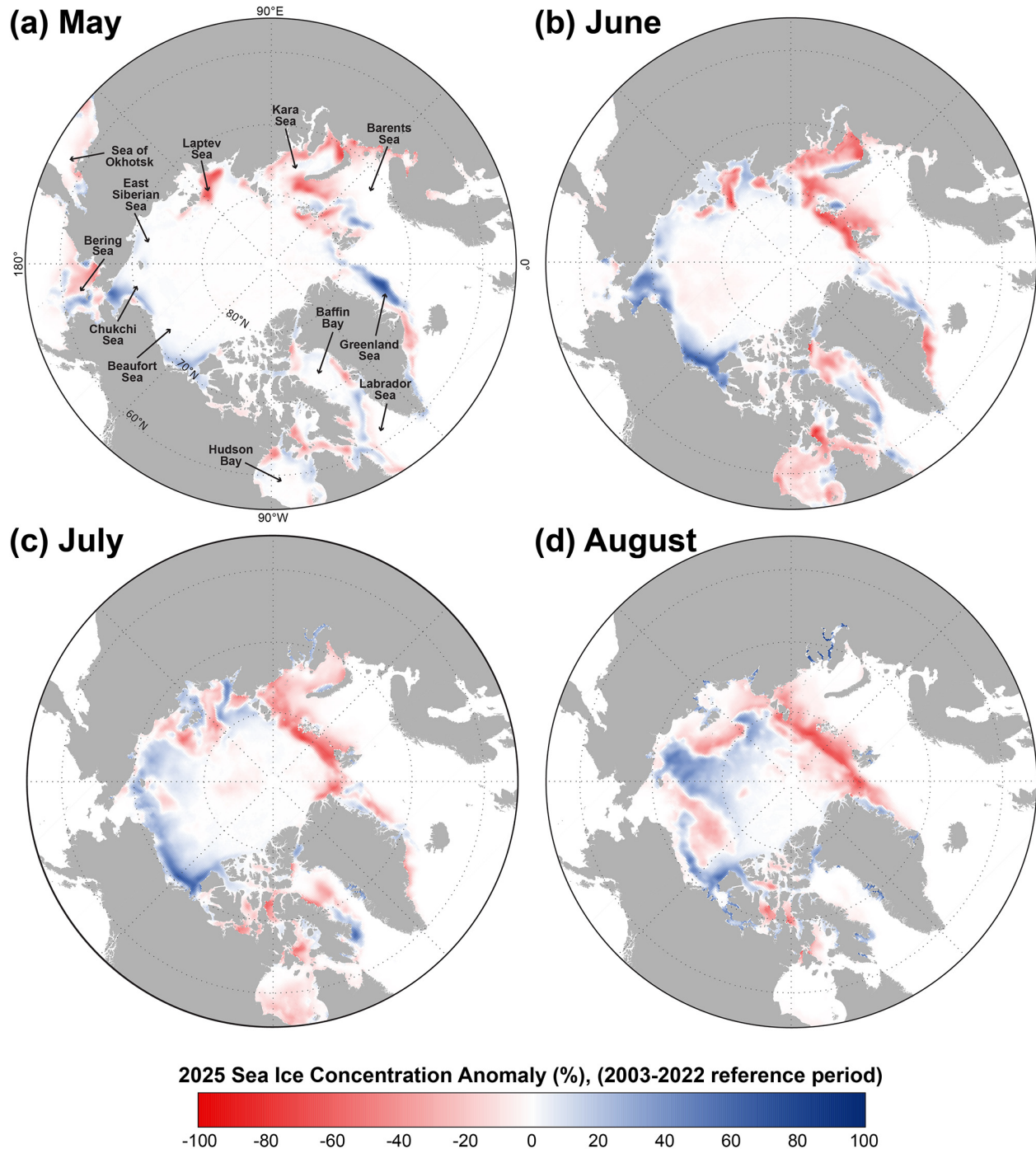


Fig. 2. Sea ice concentration anomalies (%) in 2025 (compared to a 2003-22 mean reference period) for (a) May, (b) June, (c) July, and (d) August. Data source: SSM/I and SSMIS passive microwave data, calculated using the Goddard Bootstrap (SB2) algorithm (Comiso et al. 2017).

Primary production

While chlorophyll-*a* concentrations give an estimate of the total standing stock of algal biomass, rates of primary production 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 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 increases in primary productivity appear clustered in the Norwegian Sea, Barents Sea, Kara Sea, Laptev Sea, southeastern Chukchi Sea, and northern Bering Sea south of St. Lawrence Island (Fig. 3b). Positive trends adjacent to the Eurasian coastline may reflect river-derived, light-absorbing CDOM variability rather than true productivity increases (e.g., Zoffoli et al. 2025)—a critical caveat for interpreting regional increases there. There is almost no evidence of significant negative trends in primary productivity across the Arctic (Fig. 3b). Investigations of 2025 annual primary productivity (Fig. 3c), as well as 2025 compared to the 2003-22 average (Fig. 3d), show the strongest higher-than-average annual productivity along the sea ice edge in the northern Greenland, Barents, and Kara Seas of the eastern Arctic. The strongest lower-than-average annual productivity values are juxtaposed in the western Arctic across the Chukchi and Beaufort Seas (Fig. 3d). This clearly aligns with observed hemispheric contrasts in 2025 sea ice conditions (Fig. 2), where sea ice cover was lower-than-average in the eastern Arctic and higher-than-average in the western Arctic, most notably during June (Fig. 2b), July (Fig. 2c), and August (Fig. 2d).

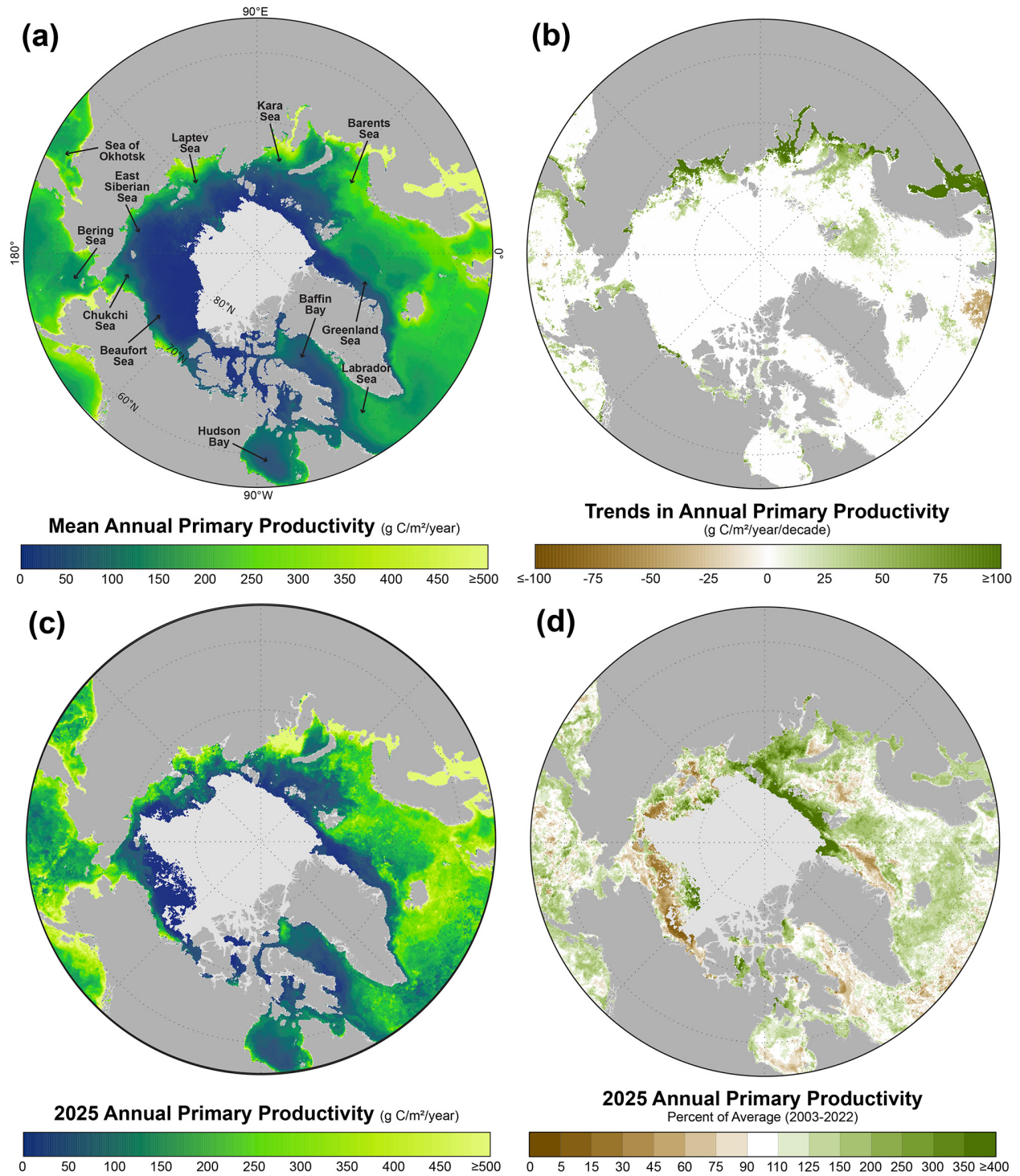


Fig. 3. For the pan-Arctic region: (a) mean annual (March-September only) primary productivity (2003-25); (b) trends in annual productivity (over 2003-25) where only those trends that are statistically significant ($p < 0.05$) are shown; (c) annual primary productivity for 2025 only; and (d) 2025 annual 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. September 2025 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 2025 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 region is confined between ~45-55° N. Our results show above-average primary productivity for 2025 in eight of the nine regions assessed, with only the Amerasian Arctic exhibiting lower-than-average values (Fig. 4, Table 1). Positive trends in primary productivity continued in all regions (except for the Amerasian Arctic) during the 2003-25 period. Those trends that are statistically significant ($p < 0.05$) occurred in six of the nine regions: Eurasian Arctic (80.2% increase), Sea of Okhotsk (24.4% increase), Bering Sea (26.3% increase), Barents Sea (33.8% increase), Hudson Bay (27.1% increase), and Baffin Bay/Labrador Sea (10.4% 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 2003-25 time period of 21.6 Tg C/yr (Mann-Kendall significance $p < 0.0001$). The percent increase over the 23-year time series is estimated to be 30.5%. In summary, while observations of primary productivity show complex interannual and spatial patterns over the 2003-25 period, we continue to observe overall positive trends across most Arctic regions.

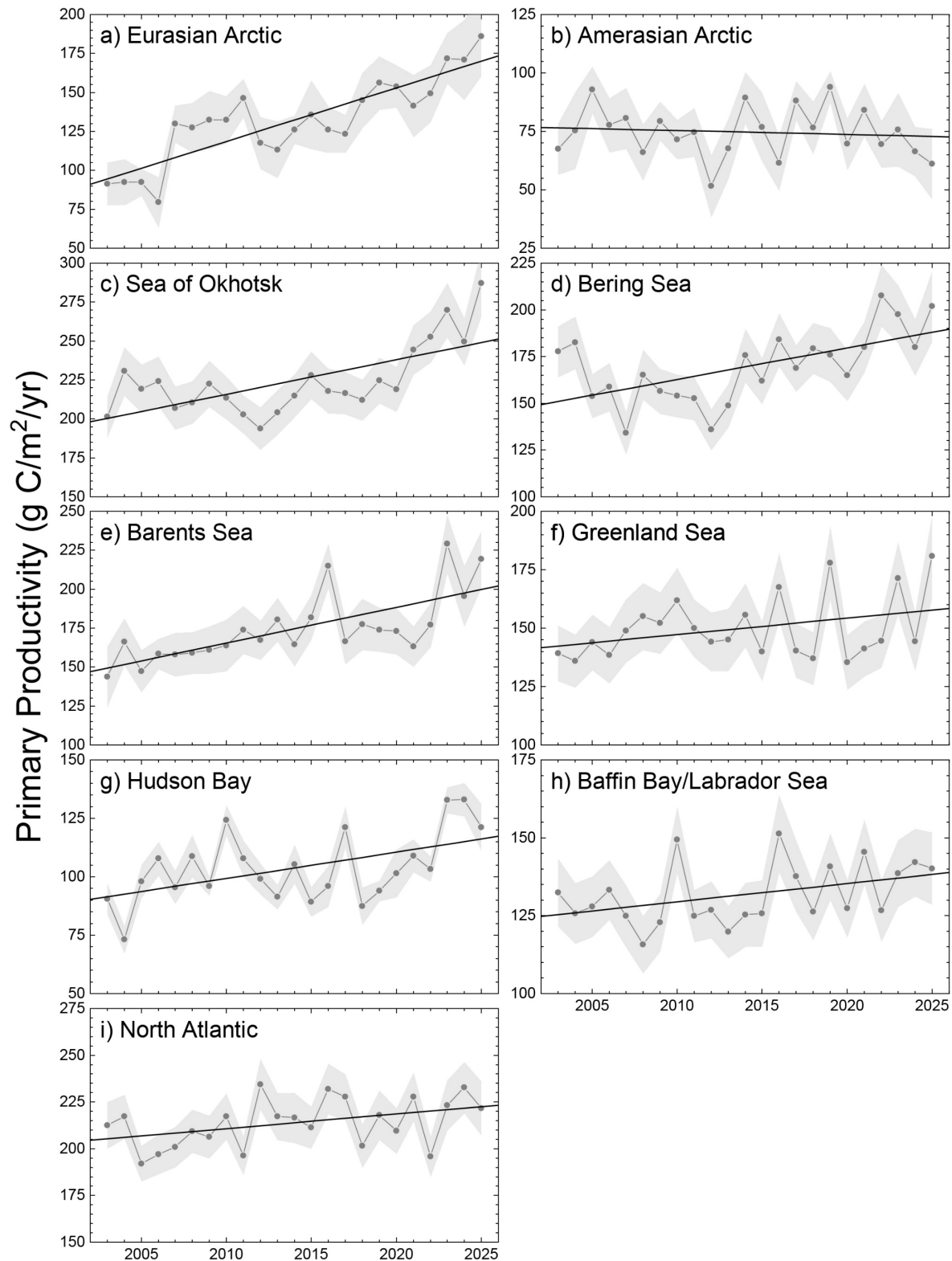


Fig. 4. Primary productivity (2003-25, March-September only) in nine different regions of the Northern Hemisphere (for a definition of the regions see Comiso 2015). The statistical significance of the trends (based on the Mann-Kendall test), p -values, and additional information regarding these data can be found in Table 1. September 2025 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 (2003-25) and primary productivity anomalies for 2025 (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 percentage change was estimated from the linear regression of the 23-year time series. The units for the Total Arctic differ because they represent annual net primary production across the Arctic (60-90° N) (as shown in Fig. 5) rather than average regional production rates (as shown in Fig. 4). September 2025 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.

Region	2003-25 Trend (g C/m ² /yr/ decade)	2003-25 Mann- Kendall <i>p</i> -value	2003-25 % Change	2025 Anomaly (g C/m ² /yr) from the 2003-22 reference period	2025 Primary Productivity (% of the 2003-22 average)
Eurasian Arctic	34.40	<0.0001	80.2	60.52	148.2
Amerasian Arctic	-1.03	0.566	-3.0	-8.60	88.6
Sea of Okhotsk	22.19	0.004	24.4	69.05	131.7
Bering Sea	17.97	0.005	26.3	46.53	128.0
Barents Sea	22.93	<0.0001	33.8	50.64	130.0
Greenland Sea	7.27	0.172	11.2	35.71	124.2
Hudson Bay	11.24	0.039	27.1	21.28	121.3
Baffin Bay/Labrador Sea	5.93	0.044	10.4	10.18	107.8
North Atlantic	7.85	0.050	8.4	9.67	104.6
Total Arctic (>60° N)	21.6*	<0.0001	30.5	478.90**	127.3

*units are Tg C/yr; **units are Tg C

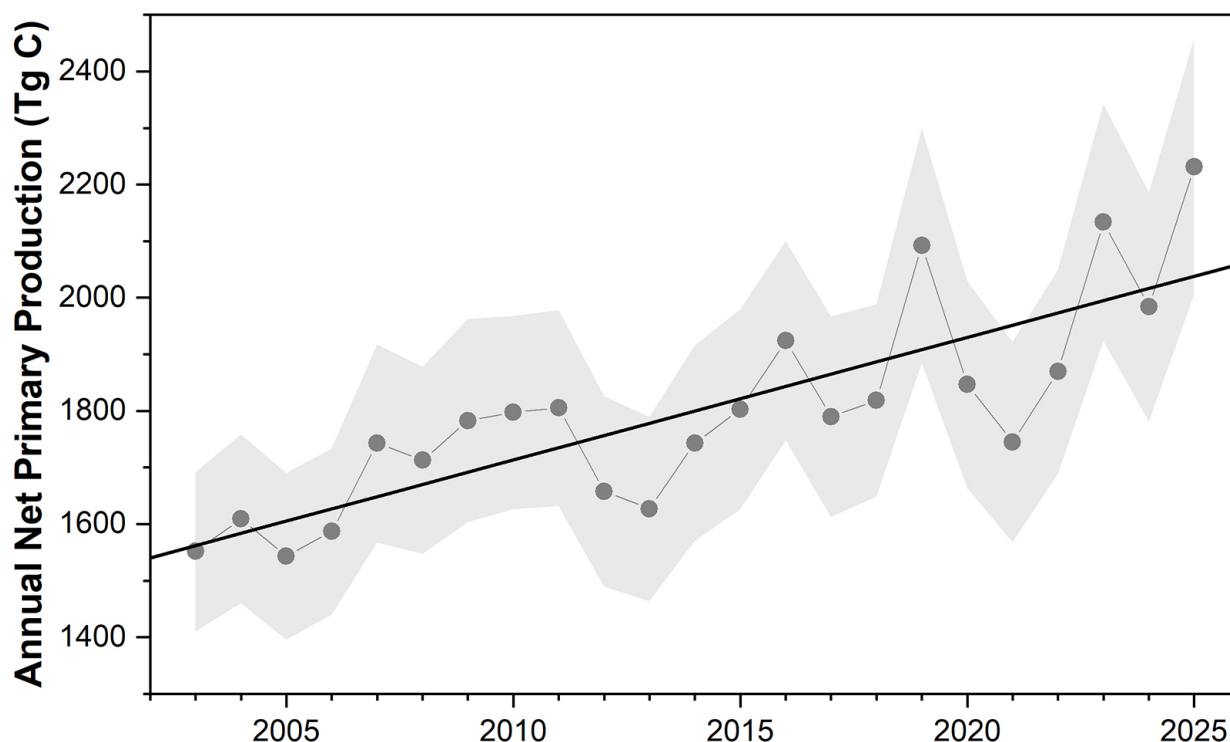


Fig. 5. Annual net primary production (2003-25, March-September only) for the Arctic region defined as 60-90° N. The trend over the 2003-25 time period is 21.6 Tg C/yr. The percentage change estimated from the linear regression over the 23-year time series is 30.5%. September 2025 chlorophyll-*a* data (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 2003-25 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 2022.0.2 (November 2024) chlor_*a* algorithm: <https://oceancolor.gsfc.nasa.gov/>. For this report, we show mean monthly chlorophyll-*a* concentrations calculated as a percentage of the 2003-22 average. This same reference period (2003-22) has been utilized for the last three consecutive Arctic Ocean Primary Productivity Arctic Report Card essays (i.e., Frey et al. 2023b; Frey et al. 2024; *this essay*) ever since the MODIS-Aqua satellite record accrued 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). Primary productivity data were derived using chlorophyll-*a* concentrations from MODIS-Aqua data (Reprocessing 2022.0.2, chlor_*a* algorithm), the NOAA 1/4° daily Optimum Interpolation Sea Surface Temperature dataset (or daily OISST), 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). We included only pixels with less than 10% sea ice concentration, balancing ice contamination concerns against capturing the productive sea ice-edge. We define annual productivity as productivity over the March-September period. The 2025 annual primary

productivity percent of average (compared to 2003-22) was calculated the same way as for chlorophyll-*a*, as described above. 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 2022.0.2 (<https://oceancolor.gsfc.nasa.gov/data/reprocessing/r2022.0.2/aqua/>) that took place in November 2024 includes revised data from 2022-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 2022 onwards.

Importantly, our estimates exclude sea ice algae and under-ice phytoplankton blooms, which can be significant (Ardyna et al. 2020). 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; Zoffoli et al. 2025). As such, in-situ observations continue to provide important overall context for changes to and drivers of primary productivity across Arctic marine ecosystems. This is particularly relevant given the vulnerabilities of satellite systems to finite temporal extents where in-situ observations can help to accurately dovetail data from different satellite platforms.

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