

Supplementary information: From Surface Warming to Vertical Phytoplankton Reorganization in the North Pacific Subtropical Gyre

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Table S1: Summary of data-processing and analytical procedures used in the North Pacific Subtropical Gyre (NPSG) analyses. Unless otherwise stated, data processing, statistical analyses, interpolation, and visualization were performed in MATLAB.

No.	Method	Processing details	Reference
1	Regional spatial averaging	Satellite variables were spatially averaged within the NPSG ROI. Sea surface temperature (SST) from Extended Reconstructed Sea Surface Temperature version 6 (ERSSTv6) was regionally averaged using cosine-of-latitude weighting to account for differences in grid-cell area with latitude. Calendar-month-specific SST outliers were removed before annual averaging.	Huang et al. (2025a, b)
2	Backscattering-based phytoplankton carbon estimation	Surface phytoplankton carbon biomass (C_{phyto}) was estimated from satellite particulate backscattering at 443 nm ($b_{\text{bp},443}$) as $C_{\text{phyto}} = 13000 (b_{\text{bp},443} - 0.00035)$, where C_{phyto} is expressed in mg C m^{-3} and $b_{\text{bp},443}$ in m^{-1} . Values of $b_{\text{bp},443} < 0.00035 \text{ m}^{-1}$ were constrained to 0.00036 m^{-1} to avoid negative C_{phyto} estimates. For BGC-Argo profiles, $b_{\text{bp},700}$ was spectrally converted to particulate backscattering at 470 nm ($b_{\text{bp},470}$) using $b_{\text{bp},470} = b_{\text{bp},700} (470/700)^{-0.78}$. Depth-resolved phytoplankton carbon biomass was then calculated as $C_{\text{phyto}} = 12128, b_{\text{bp},470} + 0.59$. Chlorophyll: C_{phyto} was calculated from temporally or vertically matched chlorophyll and C_{phyto} observations.	Behrenfeld et al. (2005); Westberry et al. (2008); Behrenfeld and Boss (2014)
3	Underwater irradiance and isolume calculation	Irradiance at depth (I_z) was calculated in MATLAB using the Beer-Lambert relationship, $I_z = \text{PAR}_{\text{surf}} \exp(-K_{\text{PAR}} z)$, where PAR_{surf} is surface photosynthetically available radiation (PAR) and K_{PAR} is the attenuation coefficient for PAR. K_{PAR} was approximated from the diffuse attenuation coefficient at 490 nm ($K_d 490$). The depths corresponding to 10%, 1%, and 0.1% of surface irradiance were subsequently calculated.	Ryther (1956); Kirk (1994); Letelier et al. (2004, 2017)
4	Profile selection and seasonal coverage screening for Biogeochemical-Argo (BGC-Argo)	BGC-Argo chlorophyll, particulate backscattering coefficient at 700 nm ($b_{\text{bp},700}$), and dissolved oxygen (DOXY) were processed independently. Profiles were restricted to 0 to 300 meter and required at least five valid observations. Platform-year records were retained when observations covered at least 10 distinct calendar months and the float trajectory entered the NPSG region of interest (ROI).	—
5	Deep chlorophyll maximum (DCM) determination	BGC-Argo chlorophyll was aggregated into 10 meter depth bins. Monthly and annual DCM depths were defined as the depth of maximum chlorophyll within the 20 to 250 meter search interval.	—
6	Apparent oxygen utilization (AOU) calculation	AOU was calculated as $\text{AOU} = O_{2,\text{sat}} - O_{2,\text{obs}}$, where $O_{2,\text{sat}}$ is dissolved oxygen concentration at saturation and $O_{2,\text{obs}}$ is observed dissolved oxygen. Oxygen saturation was calculated from the corresponding hydrographic properties. Profiles were interpolated onto a 1 m grid, monthly platform medians were averaged equally across platforms, and annual profiles required at least three valid months at each depth.	Garcia and Gordon (1992); Sarmiento and Gruber (2006); Emerson and Bushinsky (2014)

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Table S1 Continued

No.	Method	Processing details	Reference
7	Hierarchical profile aggregation for physical Argo	For physical Argo data, observations at each depth were first aggregated as monthly platform medians, followed by equal month annual platform means and equal platform yearly means. At least six represented months were required for calculation of an annual platform value. This hierarchical aggregation reduced biases caused by unequal sampling among platforms, months, and years.	—
8	Thermodynamic conversion and vertical interpolation	Physical-Argo profiles were restricted to the upper 300 m. Thermodynamic calculations were performed in MATLAB using the Gibbs SeaWater (GSW) Oceanographic Toolbox, which implements the Thermodynamic Equation of Seawater 2010 (TEOS-10). Practical Salinity and in situ temperature were converted to Absolute Salinity and Conservative Temperature, respectively, and potential density or isopycnal referenced to 0 meter (σ_0) was subsequently calculated. Valid profiles were interpolated onto a common 1 m vertical grid.	—
9	Density-threshold mixed-layer depth (MLD) and isopycnal determination	MLD was defined using σ_0 at 10 m as the near-surface reference and a density increase of 0.03 kg m^{-3} . Selected isopycnal depths were determined from the same potential-density profiles.	de Boyer Montégut et al. (2004)
10	Ocean heat content (OHC) and anomaly calculation	OHC was calculated as $\text{OHC}(z) = \rho_0 c_p \Theta(z)$, where $\rho_0 = 1025 \text{ kg m}^{-3}$ is the reference seawater density, $c_p = 3985 \text{ J kg}^{-1} \text{ K}^{-1}$ is the specific heat capacity of seawater, and Θ is Conservative Temperature. Annual OHC anomalies were calculated relative to the long-term mean at each depth.	Levitus et al. (2012); Roemmich et al. (2015)
11	Temporal aggregation and robust outlier screening	Observations occurring on the same calendar day were combined using their median. Daily outliers were identified using a 61-observation moving median and median absolute deviation (MAD), with the robust standard-deviation estimate $\sigma_{\text{robust}} = 1.4826 \text{ MAD}$ and a $3\sigma_{\text{robust}}$ threshold. At least 15 observations were required within the moving window. Monthly series were screened using a median-based threshold factor of 3 before annual averaging.	—
12	Linear trend estimation	Long-term trends were estimated using ordinary least-squares regression in MATLAB. For satellite chlorophyll, spatial trends were calculated independently at each grid cell after removal of invalid values, concentrations outside 0 to 20 mg m^{-3} , and observations exceeding three standard deviations from the grid-cell temporal mean; at least 10 valid observations were required. SST trends were calculated on the native ERSSTv6 grid.	—

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Table S1 Continued

No.	Method	Processing details	Reference
13	Breakpoint detection and model comparison	Potential temporal transitions were evaluated using a global single-breakpoint search applied to annual means. All permissible split points were tested, with a minimum of five annual observations required on each side of a candidate breakpoint. For each candidate split, separate ordinary least-squares regressions were fitted before and after the split, and the breakpoint minimizing the combined sum of squared errors (SSE) of the two regressions was selected as the best-fitting candidate. Statistical support was then evaluated using a Bai-Perron-style bootstrap supremum-F (sup-F) test and a Davies-type bootstrap maximum slope-change test, each based on 1000 residual-bootstrap replicates under the single-trend null model. The single-trend and two-segment models were additionally compared using the Akaike information criterion (AIC), corrected Akaike information criterion (AICc), and Bayesian information criterion (BIC). For consistency, ΔAIC, ΔAICc, and ΔBIC are defined as $\Delta\text{IC} = \text{IC}_{\text{single}} - \text{IC}_{\text{break}},$ where IC denotes the information criterion (AIC, AICc, or BIC). Positive values favored the two-segment model. A breakpoint was considered statistically supported only when the Bai-Perron-style and Davies-type bootstrap tests both yielded $p < 0.05$ and $\Delta\text{BIC} \geq 2$. Continuous segmented regression, AIC, and AICc were used as additional supporting diagnostics.	—
14	Dynamic-layer heat partitioning	OHC was partitioned into three dynamically defined layers: surface to MLD, MLD to euphotic-zone depth (Z_{eu}), and Z_{eu} to 300 m. MLD and monthly satellite Z_{eu} were used as layer boundaries. Grid cells intersecting either boundary were apportioned according to their exact vertical overlap with each layer.	—
15	Interpolation, smoothing, and scientific visualization	All figures and scientific visualizations were produced in MATLAB. Interpolation and smoothing used for visualization were kept separate from the observations used for statistical analyses. OHC year and depth fields were interpolated to a 2 m depth grid and a 0.25-year time grid using modified Akima (MAKIMA) interpolation. Depending on the analysis, linear or MAKIMA interpolation was applied only within observationally supported depth and time ranges. Light smoothing was used only for display, no extrapolation beyond the supported range was permitted, and unsupported gaps remained missing. Statistical analyses were performed using the cleaned observational or aggregated values rather than the interpolated display fields.	—

Table S2: Biogeochemical-Argo (BGC-Argo) platform-year chlorophyll coverage used in the vertical-profile analysis. The table summarizes the number of retained observations, number of represented calendar months, and observed depth range for each World Meteorological Organization (WMO) platform-year combination. Adequate monthly coverage indicates platform-years that satisfied the minimum temporal-coverage criterion used in the analysis.

WMO platform	Year	No. observations	No. months	Minimum depth (meter)	Maximum depth (meter)
2903860	2024	1208	12	5.52	291.91
3902559	2024	1645	10	7.30	299.81
5904655	2016	2313	12	4.30	299.80
5904655	2017	2244	12	3.90	299.80
5906040	2020	4531	12	6.61	299.53
5906040	2021	3498	10	7.02	299.48
5906502	2022	1246	12	7.26	299.30
5906516	2023	1216	12	7.32	291.91
5906516	2024	1203	12	7.35	291.93
5906529	2023	2463	12	6.96	299.31

Note: Platform numbers correspond to WMO identifiers. The number of observations represents retained valid chlorophyll observations after data filtering. Minimum and maximum depth indicate the vertical sampling range represented for each platform-year. Adequate monthly coverage indicates that the platform-year met the minimum monthly sampling requirement applied in the analysis. All retained platform-years satisfied this criterion.

Table S3: Pairwise Pearson correlations among mean vertical chlorophyll profiles derived from individual Biogeochemical-Argo (BGC-Argo) platforms in the North Pacific Subtropical Gyre (NPSG). For each platform, a mean vertical chlorophyll profile was calculated across common 10-meter depth bins, and Pearson correlation coefficients were then calculated between all platform pairs. High positive correlations indicate that spatially distributed platforms resolved similar vertical chlorophyll structure despite differences in float trajectories and sampling locations within the study region.

Platform	2903860	3902559	5904655	5906040	5906502	5906516	5906529
2903860	1	0.958	0.993	0.980	0.967	0.986	0.981
3902559	0.958	1	0.935	0.989	0.995	0.940	0.986
5904655	0.993	0.935	1	0.964	0.949	0.986	0.969
5906040	0.980	0.989	0.964	1	0.994	0.959	0.995
5906502	0.967	0.995	0.949	0.994	1	0.948	0.991
5906516	0.986	0.940	0.986	0.959	0.948	1	0.976
5906529	0.981	0.986	0.969	0.995	0.991	0.976	1

Note: Values are Pearson correlation coefficients calculated between platform-specific mean vertical chlorophyll profiles across common 10-meter depth bins. The diagonal values equal 1 because each platform is perfectly correlated with itself. Only unique off-diagonal platform pairs are statistically independent comparisons. Pairwise correlations ranged from $r = 0.935$ to $r = 0.995$, indicating highly consistent vertical chlorophyll profile shapes among the seven spatially distributed BGC-Argo platforms. These correlations assess similarity in vertical profile structure and do not imply identical absolute chlorophyll concentrations or uniform spatial sampling across the NPSG.

Table S4: Depth-resolved endpoint differences in chlorophyll, phytoplankton carbon biomass (C_{phyto}), and Chlorophyll: C_{phyto} in the North Pacific Subtropical Gyre (NPSG). Four individual endpoint differences are reported together with the mean recent-minus-early difference, calculated as the $\mu(2023, 2024) - \mu(2016, 2017)$. Depth values denote the centres of 10-meter depth bins.

Variable	Depth (m)	2023-2016	2023-2017	2024-2016	2024-2017	$\mu(2023, 2024) - \mu(2016, 2017)$
Chlorophyll	5	-0.02	-7.84×10^{-3}	-7.16×10^{-3}	1.54×10^{-3}	-7.50×10^{-3}
	15	-0.01	-8.73×10^{-3}	-3.99×10^{-3}	1.26×10^{-3}	-6.36×10^{-3}
	25	-0.01	-9.39×10^{-3}	8.33×10^{-4}	1.88×10^{-3}	-4.28×10^{-3}
	35	-0.01	-0.01	1.22×10^{-3}	-2.78×10^{-4}	-6.44×10^{-3}
	45	-0.01	-0.02	-2.32×10^{-3}	-9.37×10^{-3}	-0.01
	55	-0.02	-0.02	-1.31×10^{-3}	-3.26×10^{-3}	-9.41×10^{-3}
	65	-0.02	-0.03	1.28×10^{-3}	-9.67×10^{-3}	-0.01

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Table S4 continued

Variable	Depth (m)	2023-2016	2023-2017	2024-2016	2024-2017	$\mu(2023, 2024) - \mu(2016, 2017)$
	75	-0.03	-0.05	-8.66×10^{-3}	-0.03	-0.03
	85	-0.05	-0.10	-0.02	-0.07	-0.06
	95	-0.04	-0.10	-4.65×10^{-3}	-0.07	-0.05
	105	-0.03	-0.08	3.44×10^{-3}	-0.04	-0.04
	115	-0.02	-0.04	0.02	-4.95×10^{-3}	-0.01
	125	-0.02	-0.02	0.02	0.02	9.93×10^{-5}
	135	-0.02	-8.68×10^{-3}	0.01	0.02	7.20×10^{-4}
	145	-0.01	-0.01	7.51×10^{-3}	5.11×10^{-3}	-2.92×10^{-3}
	155	-0.02	-0.02	-6.45×10^{-3}	-4.80×10^{-3}	-0.01
	165	-0.01	-0.01	-7.87×10^{-3}	-6.97×10^{-3}	-9.27×10^{-3}
	175	-0.02	-9.42×10^{-3}	-0.02	-5.87×10^{-3}	-0.01
	185	-0.02	-9.43×10^{-3}	-0.02	-8.04×10^{-3}	-0.01
	195	-0.01	-7.96×10^{-3}	-0.01	-6.55×10^{-3}	-9.58×10^{-3}
	205	-0.01	-5.28×10^{-3}	-0.01	-5.74×10^{-3}	-9.26×10^{-3}
	215	-8.75×10^{-3}	-2.15×10^{-3}	-9.40×10^{-3}	-2.80×10^{-3}	-5.77×10^{-3}
	225	-6.43×10^{-3}	3.23×10^{-4}	-7.87×10^{-3}	-1.12×10^{-3}	-3.77×10^{-3}
	235	-3.35×10^{-3}	9.69×10^{-5}	-5.07×10^{-3}	-1.62×10^{-3}	-2.49×10^{-3}
	245	-2.01×10^{-3}	1.14×10^{-3}	-3.30×10^{-3}	-1.48×10^{-4}	-1.08×10^{-3}
	255	3.21×10^{-4}	9.21×10^{-4}	-1.08×10^{-3}	-4.76×10^{-4}	-7.78×10^{-5}
	265	6.21×10^{-4}	1.82×10^{-3}	-1.03×10^{-3}	1.75×10^{-4}	3.98×10^{-4}
	275	1.82×10^{-3}	1.37×10^{-3}	4.26×10^{-4}	-2.43×10^{-5}	9.00×10^{-4}
	285	1.90×10^{-3}	2.50×10^{-3}	-6.32×10^{-4}	-3.19×10^{-5}	9.32×10^{-4}
	295	2.20×10^{-3}	2.35×10^{-3}	3.02×10^{-4}	4.52×10^{-4}	1.33×10^{-3}
C_{phyto}	5	-0.42	-0.14	-0.02	0.26	-0.08
	15	0.14	-0.17	1.11	0.80	0.47
	25	0.43	-0.22	1.00	0.35	0.39
	35	0.57	-0.40	1.34	0.37	0.47
	45	0.28	-0.46	0.80	0.05	0.17
	55	0.35	-0.39	0.83	0.09	0.22
	65	0.12	-0.66	0.62	-0.16	-0.02
	75	0.11	-0.53	0.58	-0.06	0.02
	85	-0.15	-0.71	0.45	-0.11	-0.13
	95	-0.25	-1.01	0.34	-0.43	-0.34
	105	-0.40	-0.76	0.08	-0.27	-0.34
	115	-0.66	-0.59	0.10	0.17	-0.24
	125	-0.46	-0.89	0.25	-0.18	-0.32
	135	-0.57	-0.85	0.02	-0.26	-0.42

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Table S4 continued

Variable	Depth (m)	2023-2016	2023-2017	2024-2016	2024-2017	$\mu(2023, 2024) - \mu(2016, 2017)$
	145	-0.30	-0.29	0.29	0.31	3.13×10^{-3}
	155	-0.66	-0.58	-0.07	0.01	-0.32
	165	-0.36	-0.38	-0.10	-0.13	-0.24
	175	-0.91	-0.67	-0.63	-0.39	-0.65
	185	-0.80	-0.60	-0.30	-0.09	-0.45
	195	-0.82	-0.63	-0.46	-0.27	-0.54
	205	-1.01	-0.69	-0.59	-0.27	-0.64
	215	-0.84	-0.56	-0.62	-0.34	-0.59
	225	-0.69	-0.71	-0.38	-0.39	-0.54
	235	-0.80	-0.58	-0.50	-0.28	-0.54
	245	-0.62	-0.45	-0.27	-0.10	-0.36
	255	-0.78	-0.64	-0.57	-0.42	-0.60
	265	-0.63	-0.47	-0.44	-0.27	-0.45
	275	-0.66	-0.46	-0.32	-0.12	-0.39
	285	-0.73	-0.57	-0.44	-0.28	-0.51
	295	-0.62	-0.45	-0.30	-0.13	-0.38
Chlorophyll: C_{phyt}	5	-1.74×10^{-3}	-7.82×10^{-4}	-1.03×10^{-3}	-7.60×10^{-5}	-9.07×10^{-4}
	15	-1.55×10^{-3}	-8.47×10^{-4}	-9.03×10^{-4}	-1.95×10^{-4}	-8.75×10^{-4}
	25	-1.23×10^{-3}	-9.31×10^{-4}	-4.18×10^{-4}	-1.19×10^{-4}	-6.75×10^{-4}
	35	-1.51×10^{-3}	-1.24×10^{-3}	-6.09×10^{-4}	-3.43×10^{-4}	-9.26×10^{-4}
	45	-1.50×10^{-3}	-1.54×10^{-3}	-8.37×10^{-4}	-8.73×10^{-4}	-1.19×10^{-3}
	55	-1.58×10^{-3}	-1.59×10^{-3}	-5.89×10^{-4}	-5.97×10^{-4}	-1.09×10^{-3}
	65	-1.84×10^{-3}	-2.34×10^{-3}	-5.15×10^{-4}	-1.02×10^{-3}	-1.43×10^{-3}
	75	-2.68×10^{-3}	-4.74×10^{-3}	-1.03×10^{-3}	-3.09×10^{-3}	-2.88×10^{-3}
	85	-4.03×10^{-3}	-8.20×10^{-3}	-1.73×10^{-3}	-5.90×10^{-3}	-4.97×10^{-3}
	95	-3.72×10^{-3}	-8.82×10^{-3}	-7.52×10^{-4}	-5.86×10^{-3}	-4.79×10^{-3}
	105	-2.42×10^{-3}	-5.67×10^{-3}	5.09×10^{-4}	-2.74×10^{-3}	-2.58×10^{-3}
	115	-7.53×10^{-4}	-2.63×10^{-3}	2.05×10^{-3}	1.76×10^{-4}	-2.89×10^{-4}
	125	3.23×10^{-5}	-9.93×10^{-5}	2.77×10^{-3}	2.64×10^{-3}	1.34×10^{-3}
	135	-1.06×10^{-3}	8.79×10^{-6}	1.21×10^{-3}	2.29×10^{-3}	6.11×10^{-4}
	145	-8.72×10^{-4}	-8.47×10^{-4}	6.95×10^{-4}	7.19×10^{-4}	-7.63×10^{-5}
	155	-1.85×10^{-3}	-1.59×10^{-3}	-6.81×10^{-4}	-4.17×10^{-4}	-1.14×10^{-3}
	165	-1.04×10^{-3}	-9.84×10^{-4}	-8.32×10^{-4}	-7.72×10^{-4}	-9.08×10^{-4}
	175	-1.58×10^{-3}	-8.36×10^{-4}	-1.36×10^{-3}	-6.11×10^{-4}	-1.10×10^{-3}
	185	-2.08×10^{-3}	-9.96×10^{-4}	-2.05×10^{-3}	-9.73×10^{-4}	-1.52×10^{-3}
	195	-1.58×10^{-3}	-9.00×10^{-4}	-1.49×10^{-3}	-8.05×10^{-4}	-1.19×10^{-3}
	205	-1.52×10^{-3}	-6.11×10^{-4}	-1.65×10^{-3}	-7.35×10^{-4}	-1.13×10^{-3}

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Table S4 continued

Variable	Depth (m)	2023-2016	2023-2017	2024-2016	2024-2017	$\mu(2023, 2024) - \mu(2016, 2017)$
	215	-1.13×10^{-3}	-2.64×10^{-4}	-1.25×10^{-3}	-3.80×10^{-4}	-7.55×10^{-4}
	225	-8.19×10^{-4}	1.48×10^{-4}	-1.07×10^{-3}	-1.08×10^{-4}	-4.63×10^{-4}
	235	-3.60×10^{-4}	6.29×10^{-5}	-6.55×10^{-4}	-2.33×10^{-4}	-2.96×10^{-4}
	245	-2.61×10^{-4}	2.29×10^{-4}	-4.94×10^{-4}	-4.64×10^{-6}	-1.33×10^{-4}
	255	9.84×10^{-5}	1.80×10^{-4}	-1.33×10^{-4}	-5.13×10^{-5}	2.36×10^{-5}
	265	1.06×10^{-4}	3.18×10^{-4}	-1.60×10^{-4}	5.12×10^{-5}	7.88×10^{-5}
	275	3.42×10^{-4}	2.77×10^{-4}	8.54×10^{-5}	2.06×10^{-5}	1.81×10^{-4}
	285	3.82×10^{-4}	4.41×10^{-4}	-3.96×10^{-5}	1.93×10^{-5}	2.01×10^{-4}
	295	4.08×10^{-4}	4.26×10^{-4}	8.31×10^{-5}	1.01×10^{-4}	2.54×10^{-4}

Note: Endpoint differences were calculated for matched calendar months at each depth bin. The final column represents $\mu(2023, 2024) - \mu(2016, 2017)$. Negative values indicate lower values during the recent period, whereas positive values indicate higher values. Chlorophyll differences are expressed in mg m^{-3} , C_{phyto} differences in mg C m^{-3} , and Chlorophyll: C_{phyto} differences in $\text{mg Chlorophyll (mg C)}^{-1}$. Depth values correspond to the centres of 10-meter depth bins.

Table S5: Depth-specific annual trends in chlorophyll and microbial cell abundances at Hawaii Ocean Time-series (HOT) Station ALOHA from 1998 to 2024. Linear trends were estimated independently at each nominal sampling depth using ordinary least-squares regression. Trends are reported in absolute units and as relative rates of change ($\% \text{ yr}^{-1}$), calculated from the same annual concentration or abundance series. Unadjusted p -values and false discovery rate (FDR)-adjusted p -values are reported. The 10 m depth was excluded because insufficient observations were available.

Variable	Depth (m)	Absolute trend (yr^{-1})	Relative trend ($\% \text{ yr}^{-1}$)	p	FDR p
Chlorophyll	5	4.87×10^{-5}	+0.055	0.870	0.890
	25	-4.16×10^{-5}	-0.045	0.890	0.890
	45	6.71×10^{-3}	+9.062	0.086	0.343
	75	5.08×10^{-4}	+0.316	0.317	0.633
	100	1.40×10^{-2}	+11.316	0.058	0.343
	125	9.32×10^{-4}	+0.545	0.156	0.415
	150	-8.67×10^{-4}	-2.101	0.883	0.890
	175	-1.13×10^{-4}	-0.314	0.623	0.890

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Table S5 continued

Variable	Depth (m)	Absolute trend (yr ⁻¹)	Relative trend (% yr ⁻¹)	<i>p</i>	FDR <i>p</i>
<i>Prochlorococcus</i>	5	3.58×10^2	+0.232	0.832	0.832
	25	5.78×10^2	+0.360	0.743	0.832
	45	4.18×10^2	+0.242	0.823	0.832
	75	-1.37×10^3	-0.748	0.414	0.828
	100	-9.63×10^2	-0.754	0.414	0.828
	125	-1.91×10^2	-0.362	0.753	0.832
	150	-2.61×10^2	-1.521	0.144	0.575
	175	-1.51×10^2	-2.808	0.029	0.228
<i>Synechococcus</i>	5	-22.89	-1.555	0.124	0.142
	25	-30.19	-1.976	0.040	0.053
	45	-32.04	-1.951	0.039	0.053
	75	-33.19	-1.825	0.031	0.053
	100	-22.66	-2.402	0.021	0.053
	125	-3.79	-1.387	0.577	0.577
	150	-5.34	-8.022	0.008	0.031
	175	-5.04	-16.517	9.61×10^{-4}	7.69×10^{-3}
Picoeukaryotes	5	-11.13	-1.273	0.165	0.658
	25	-9.32	-1.062	0.259	0.667
	45	-13.61	-1.414	0.160	0.658
	75	-6.79	-0.652	0.549	0.667
	100	+8.28	+0.620	0.573	0.667
	125	+11.73	+1.072	0.369	0.667
	150	+3.93	+0.751	0.583	0.667
	175	-0.86	-0.425	0.759	0.759

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Table S5 continued

Variable	Depth (m)	Absolute trend (yr ⁻¹)	Relative trend (% yr ⁻¹)	<i>p</i>	FDR <i>p</i>
Heterotrophic bacteria	5	-6.30×10^3	-1.499	0.066	0.237
	25	-5.75×10^3	-1.356	0.108	0.237
	45	-6.16×10^3	-1.433	0.090	0.237
	75	-5.36×10^3	-1.332	0.118	0.237
	100	-3.64×10^3	-1.064	0.227	0.237
	125	-3.18×10^3	-1.142	0.200	0.237
	150	-2.28×10^3	-1.040	0.237	0.237
	175	-2.24×10^3	-1.217	0.201	0.237

Note: Relative trends were calculated from the same annual concentration or abundance series as the absolute trends as

$$\text{Relative trend (\% yr}^{-1}\text{)} = \frac{\text{slope}}{\text{temporal mean}} \times 100.$$

and therefore represent relative rates of change rather than relative community contribution. Bold FDR-adjusted *p*-values indicate trends remaining significant after FDR correction ($p_{\text{FDR}} < 0.05$). Chlorophyll absolute trends are expressed in $\text{mg m}^{-3} \text{yr}^{-1}$, whereas microbial absolute trends are expressed in the corresponding cell-abundance units yr^{-1} . Statistical significance is identical for the absolute and relative representations because both are derived from the same regression.

Table S6: Breakpoint timing, statistical support, trend characteristics, and single-sensor sensitivity analyses for biological and upper-ocean physical variables in the North Pacific Subtropical Gyre (NPSG). The analyses include phytoplankton carbon (C_{phyto}), the chlorophyll-to-phytoplankton-carbon ratio (Chlorophyll: C_{phyto}), mixed-layer depth (MLD), Conservative Temperature (CT) and Absolute Salinity (AS), Potential density anomaly referenced to the surface (σ_0) and ocean heat content (OHC) within three vertically defined layers. Breakpoints were identified using a global one-break minimum-sum-of-squared-errors (SSE) search. Statistical support was evaluated using a Bai-Perron-style bootstrap sup- F test, a Davies-type bootstrap maximum slope-change test, and Bayesian information criterion (BIC) model comparison, with Akaike information criterion (AIC), corrected Akaike information criterion (AICc), and continuous segmented regression used as additional supporting diagnostics. Breakpoint uncertainty was estimated using residual-bootstrap resampling.

(a) Breakpoint timing and observed changes						
Variable	Breakpoint	Bootstrap 95% CI	Continuous segmented break	Value before	Value after	Percent change
C_{phyto}	2015-2016	2015.5-2015.5	2012-2013	18.36	14.45	−21.17%
Chlorophyll: C_{phyto}	2017-2018	2014.0-2017.5	2012-2013	0.003	0.006	+69.76%
MLD	2013-2014	2013.5-2013.5	2007-2008	49.02 m	38.51 m	−21.46%
CT, surface-MLD	2007-2008	2007.5-2014.5	2008-2009	26.53 °C	26.74 °C	+0.82%
CT, MLD- Z_{eu}	2013-2014	2008.5-2015.5	2011-2012	25.19 °C	24.84 °C	−1.41%
CT, Z_{eu} -300 m	2013-2014	2013.5-2014.0	2007-2008	18.82 °C	18.07 °C	−3.99%
AS, surface-MLD	2016-2017	2016.5-2016.5	2019-2020	35.13 g kg ^{−1}	35.03 g kg ^{−1}	−0.28%
AS, MLD- Z_{eu}	2015-2016	2015.5-2015.5	2012-2013	35.37 g kg ^{−1}	35.25 g kg ^{−1}	−0.33%
AS, Z_{eu} -300 m	2015-2016	2012.0-2015.5	2012-2013	34.99 g kg ^{−1}	34.95 g kg ^{−1}	−0.14%
σ_0 , surface-MLD	2018-2019	2015.5-2019.5	2019-2020	22.72 kg m ^{−3}	22.53 kg m ^{−3}	−0.79%
σ_0 , MLD- Z_{eu}	2008-2009	2007.5-2016.5	2007-2008	23.42 kg m ^{−3}	23.634 kg m ^{−3}	+0.90%
σ_0 , Z_{eu} -300 m	2013-2014	2013.5-2013.5	2007-2008	24.91 kg m ^{−3}	25.07 kg m ^{−3}	+0.67%
$\Delta\sigma_0$, 10 m- Z_{eu}	2013-2014	2013.5-2013.5	2007-2008	0.84 kg m ^{−3}	1.13 kg m ^{−3}	+34.37%
Mean $d\sigma_0/dz$, 10 m- Z_{eu}	2013-2014	2013.5-2013.5	2007-2008	0.008 kg m ^{−3}	0.011 kg m ^{−3}	+35.20%
Fitted $d\sigma_0/dz$, 10 m- Z_{eu}	2013-2014	2013.5-2013.5	2007-2008	0.008 kg m ^{−3}	0.011 kg m ^{−3}	+35.16%
OHC, surface-MLD	2007-2008	2007.5-2016.5	2008-2009	0.108 GJ m ^{−3}	0.109 GJ m ^{−3}	+0.82%
OHC, MLD- Z_{eu}	2013-2014	2008.5-2015.5	2011-2012	0.103 GJ m ^{−3}	0.101 GJ m ^{−3}	−1.41%
OHC, Z_{eu} -300 m	2013-2014	2013.5-2013.5	2007-2008	0.077 GJ m ^{−3}	0.074 GJ m ^{−3}	−3.99%

(b) Formal breakpoint tests and information-criterion model comparison						
Variable	sup- F p	Davies p	ΔAIC	ΔAICc	ΔBIC	Supported
C_{phyto}	< 0.001	< 0.001	53.60	50.44	49.71	Yes
Chlorophyll: C_{phyto}	< 0.001	< 0.001	23.84	20.69	19.95	Yes
MLD	0.002	0.067	22.03	17.76	18.75	Yes
CT, surface-MLD	0.01	0.005	11.44	7.17	8.17	Yes
CT, MLD- Z_{eu}	0.01	0.005	17.03	12.75	13.76	Yes
CT, Z_{eu} -300 m	0.005	0.005	21.45	17.18	18.18	Yes
AS, surface-MLD	0.005	0.07	14.09	9.82	10.82	Yes

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Table S6 continued

Variable	Breakpoint	Bootstrap 95% CI	Continuous segmented break	Value before	Value after	Percent change
AS, MLD- Z_{eu}	0.005	0.124	17.64	13.37	14.37	Yes
AS, Z_{eu} -300 m	0.005	0.005	20.95	16.68	17.67	Yes
σ_0 , surface-MLD	0.005	0.005	14.84	10.57	11.57	Yes
σ_0 , MLD- Z_{eu}	0.045	0.01	6.34	2.07	3.06	Yes
σ_0 , Z_{eu} -300 m	0.005	0.005	18.39	14.13	15.12	Yes
$\Delta\sigma_0$, 10 m- Z_{eu}	0.005	0.06	21.51	17.24	18.24	Yes
Mean $d\sigma_0/dz$, 10 m- Z_{eu}	0.005	0.035	22.09	17.82	18.82	Yes
Fitted $d\sigma_0/dz$, 10 m- Z_{eu}	0.005	0.035	22.09	17.82	18.82	Yes
OHC, surface-MLD	0.005	0.005	11.44	7.17	8.17	Yes
OHC, MLD- Z_{eu}	0.005	0.005	17.03	12.75	13.75	Yes
OHC, Z_{eu} -300 m	0.005	0.005	21.45	17.18	18.18	Yes

Note: The bootstrap 95% confidence interval (CI) describes uncertainty in the estimated breakpoint position; a narrow interval indicates that the breakpoint timing was consistently recovered across bootstrap resamples, whereas a broad interval indicates greater uncertainty in its timing. The Bai-Perron-style bootstrap sup- F test evaluates whether allowing a structural break provides a significantly better fit than a single linear trend. The reported bootstrap p -value is the empirical probability of obtaining a sup- F statistic at least as large as that observed under the null hypothesis of no breakpoint, $p < 0.05$ was considered statistically significant. The Davies-type bootstrap test independently evaluates evidence for a change in slope within a continuous segmented-regression framework, with $p < 0.05$ likewise considered significant.

AIC, AICc, and BIC compare the relative support for the single-linear and breakpoint models, with lower information-criterion values indicating the preferred model. AICc is the small-sample corrected form of AIC and is particularly relevant for the shorter annual records. For consistency, ΔAIC , $\Delta AICc$, and ΔBIC are defined as

$$\Delta IC = IC_{\text{single}} - IC_{\text{break}},$$

where IC denotes the information criterion (AIC, AICc, or BIC). Positive values favour the breakpoint model, whereas negative values favour the single-linear model. For ΔBIC , values < 2 indicate little or ambiguous evidence, values of approximately 2-6 indicate positive evidence, 6-10 indicate strong evidence, and values > 10 indicate very strong evidence for the model with the lower BIC.

The ‘‘Supported’’ classification used here follows the predefined analysis criterion: a breakpoint was classified as supported when either the Bai-Perron-style bootstrap sup- F test was significant ($p < 0.05$) or the breakpoint model had $\Delta BIC \geq 2$. The Davies-type test is reported as an additional diagnostic and was not used to determine this binary classification.

Table S7: Annual apparent oxygen utilization (AOU) characteristics in the North Pacific Subtropical Gyre (NPSG) for years with complete annual observational coverage. Annual AOU values were calculated for the mixed layer (0-MLD), the layer between the mixed-layer depth (MLD) and euphotic-zone depth (Z_{eu}), the layer from Z_{eu} to 300 m, and within ± 5 m of the deep chlorophyll maximum (DCM). Annual statistics were calculated from observed months only. The 2021 and 2022 observations were retained for the monthly analysis but were not used to calculate annual AOU statistics.

(a) Annual mean AOU and vertical boundaries							
Year	MLD (m)	DCM (m)	Z_{eu} (m)	$\text{AOU}_{0-\text{MLD}}$	$\text{AOU}_{\text{MLD}-Z_{\text{eu}}}$	$\text{AOU}_{Z_{\text{eu}}-300}$	$\text{AOU}_{\text{DCM}\pm 5}$
2020	43.21	115	109.38	−1.98	−1.62	42.62	12.31
2023	44.23	115	107.62	−1.29	−0.22	45.57	11.19
2024	40.15	115	108.66	−0.86	−0.90	40.72	14.75

(b) Annual AOU inventory tendencies				
Year	0-MLD	MLD- Z_{eu}	Z_{eu} -300 m	DCM ± 5 m
2020	−9.88	−28.90	−30.56	−5.33
2023	0.20	−5.34	−7.09	−0.69
2024	0.22	1.36	−6.97	0.17

Note: AOU is apparent oxygen utilization and is expressed in $\mu\text{mol kg}^{-1}$ in panel (a). Negative AOU indicates oxygen supersaturation relative to atmospheric equilibrium, whereas positive AOU indicates oxygen below atmospheric saturation. MLD denotes mixed-layer depth, DCM denotes deep chlorophyll maximum depth, and Z_{eu} denotes euphotic-zone depth. Annual values were calculated from observed months only. Although short internal gaps of up to three months were linearly interpolated for the monthly analysis and visualization, interpolated months were not used to generate the annual statistics reported here. Consequently, 2021 and 2022 are not included in the annual summary.

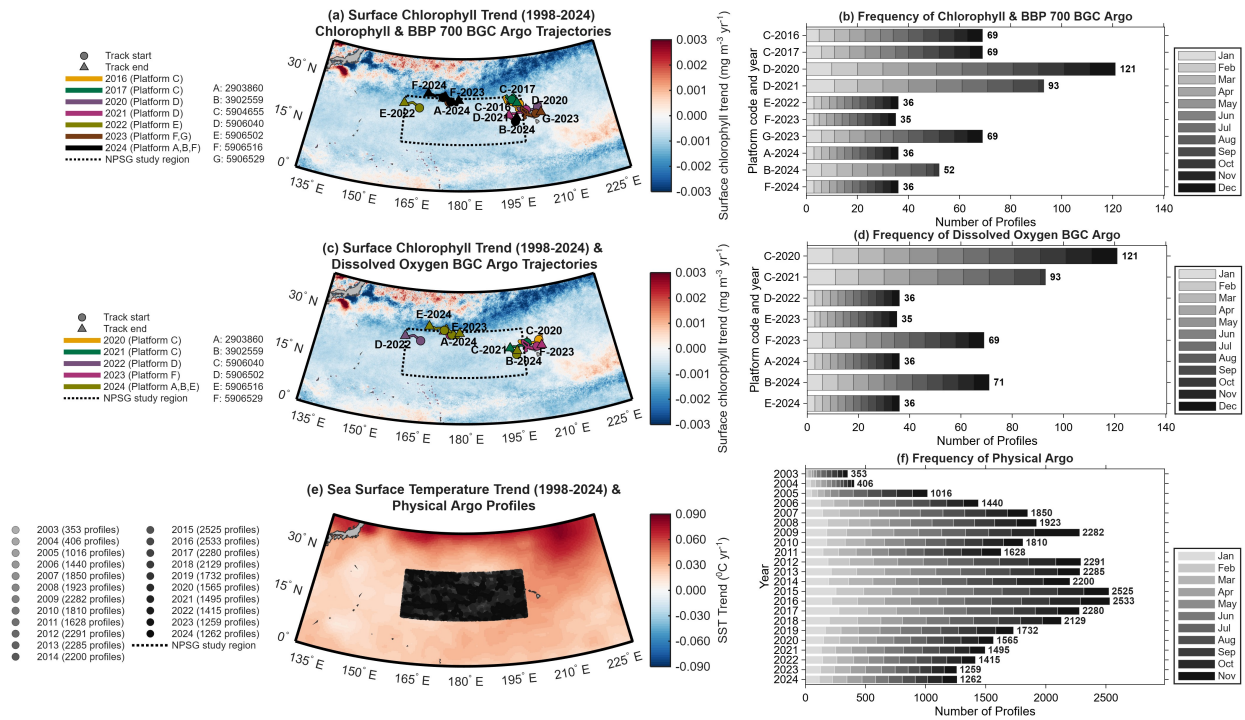


Figure S1. Spatial and temporal coverage of biogeochemical Argo (BGC-Argo) and physical-Argo observations used in the North Pacific Subtropical Gyre (NPSG) (a, c, e) Spatial coverage of the retained Argo observations. Panels (a) and (c) show satellite surface chlorophyll trends from 1998 to 2024 overlaid with BGC-Argo trajectories containing chlorophyll and particulate backscattering at 700 nm ($b_{bp,700}$), and dissolved oxygen (DOXY), respectively. Panel (e) shows the Extended Reconstructed Sea Surface Temperature version 6 (ERSSTv6) (Huang et al. (2025a, b)) trend from 1998 to 2024 overlaid with retained physical Argo profile locations. Chlorophyll and sea surface temperature (SST) trends were estimated using ordinary least-squares regression, with the ERSSTv6 trend field interpolated to a 0.5° grid for visualization only. Red and blue shading indicate positive and negative trends, respectively. In panels (a) and (c), track colours indicate year, circles and triangles denote the first and last retained profiles, and letters identify individual platforms. In panel (e), profile locations progress from light to dark grey for earlier to more recent years. The dashed box denotes the NPSG study region ($14\text{--}28^\circ\text{N}$, $160\text{--}200^\circ\text{E}$). **(b, d, f)** Frequency of Monthly profile distributions corresponding to panels (a), (c), and (e), respectively. Stacked grey-scale segments indicate the monthly contribution to each platform-year or year, and numbers at the end of each bar show the total number of retained profiles.

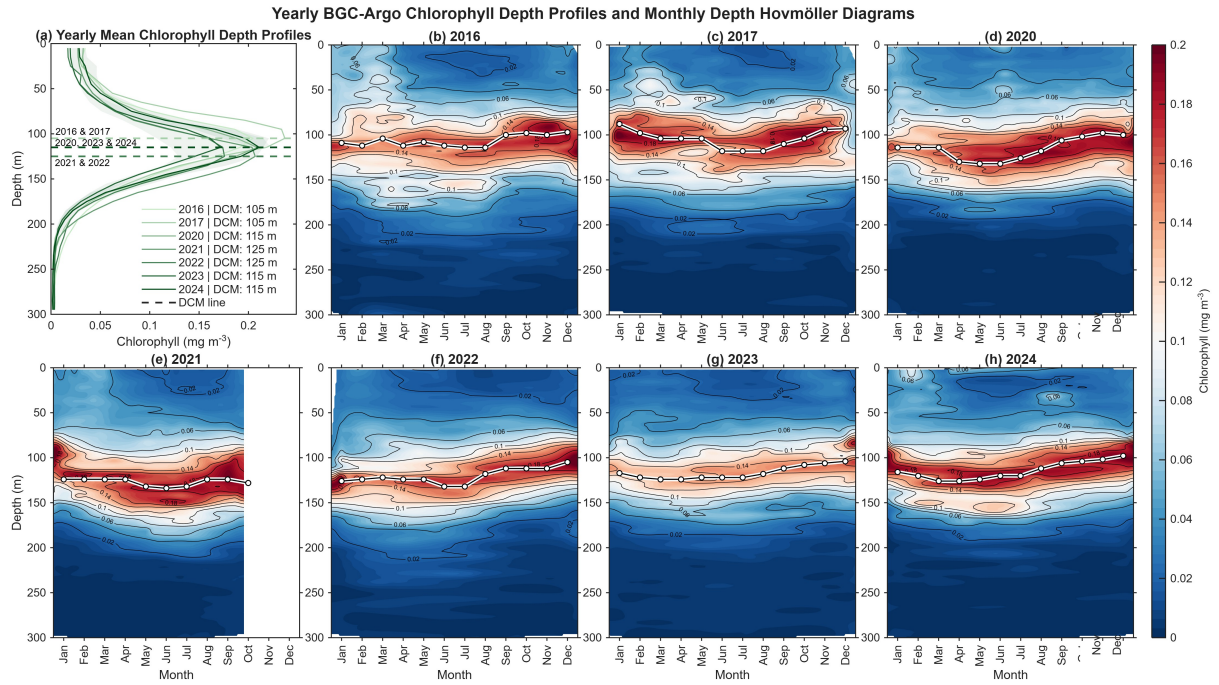


Figure S2. Yearly and monthly vertical chlorophyll structure derived from biogeochemical Argo (BGC-Argo) observations in the North Pacific Subtropical Gyre (NPSG). (a) Annual mean chlorophyll depth profiles for 2016, 2017, and 2020-2024. Profiles were aggregated onto 10 meter depth bins and averaged by year. Green lines progress from light to dark for earlier to more recent years. Horizontal dashed lines indicate the corresponding annual deep chlorophyll maximum (DCM) depths, defined as the depth of maximum chlorophyll within the DCM search range; annual DCM depths are reported in the legend. **(b-h)** Monthly depth and time distributions of chlorophyll for **(b)** 2016, **(c)** 2017, **(d)** 2020, **(e)** 2021, **(f)** 2022, **(g)** 2023, and **(h)** 2024. Colours indicate chlorophyll concentration, with blue representing lower and red representing higher values, and contours show concentration magnitude. The black line with open circles traces the monthly DCM depth, defined as the depth of maximum monthly chlorophyll within the vertical search range. For 2021, monthly observations were available only through October.

HOT Station ALOHA depth-specific biological trends

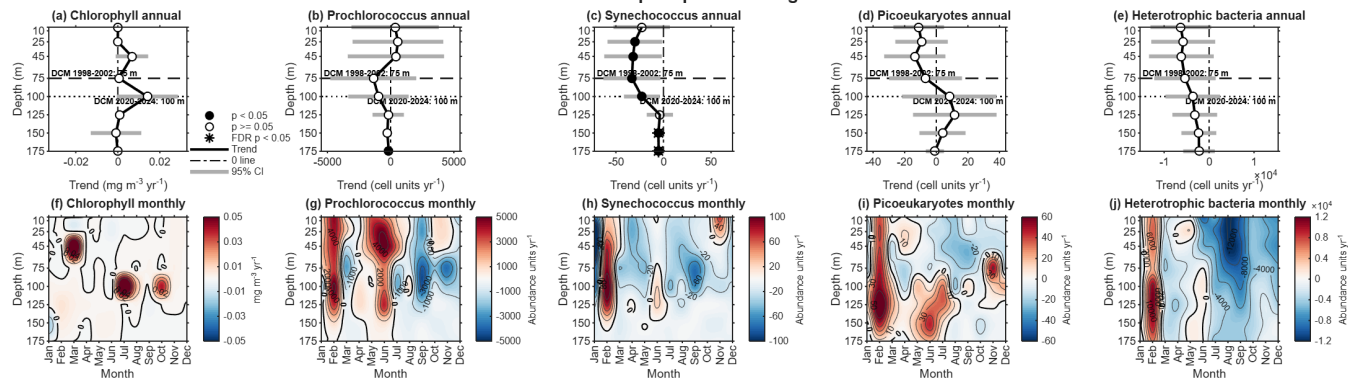


Figure S3. Depth-resolved annual and monthly biological trends at Station ALOHA from 1998 to 2024. (a-e) Annual depth-specific trends in (a) chlorophyll, (b) *Prochlorococcus*, (c) *Synechococcus*, (d) picoeukaryotes, and (e) heterotrophic bacteria. Observations were assigned to nominal sampling depths and aggregated first as monthly medians and then calculated the annual mean. Linear trends were estimated independently at each depth using ordinary least-squares regression over 1998 to 2024, requiring at least 15 valid years. Grey horizontal bars indicate the 95% confidence intervals (CI) of the trend slopes, and the vertical dash-dotted line indicates zero trend. Open circles indicate non-significant trends ($p \geq 0.05$), filled circles indicate significant unadjusted trends ($p < 0.05$), and asterisks indicate trends remaining significant after false discovery rate (FDR) correction ($p_{\text{FDR}} < 0.05$). Dashed and dotted horizontal lines indicate the deep chlorophyll maximum (DCM) depths derived from the mean annual chlorophyll profiles for the early (1998 to 2002) and recent (2020 to 2024) five-year periods, respectively. (f-j) Month-depth distributions of linear trends for the same variables: (f) chlorophyll, (g) *Synechococcus*, (h) *Prochlorococcus*, (i) picoeukaryotes, and (j) heterotrophic bacteria. Red shading indicates positive trends, blue shading negative trends, and the black contour denotes zero trend and additional contours indicate trend magnitude.

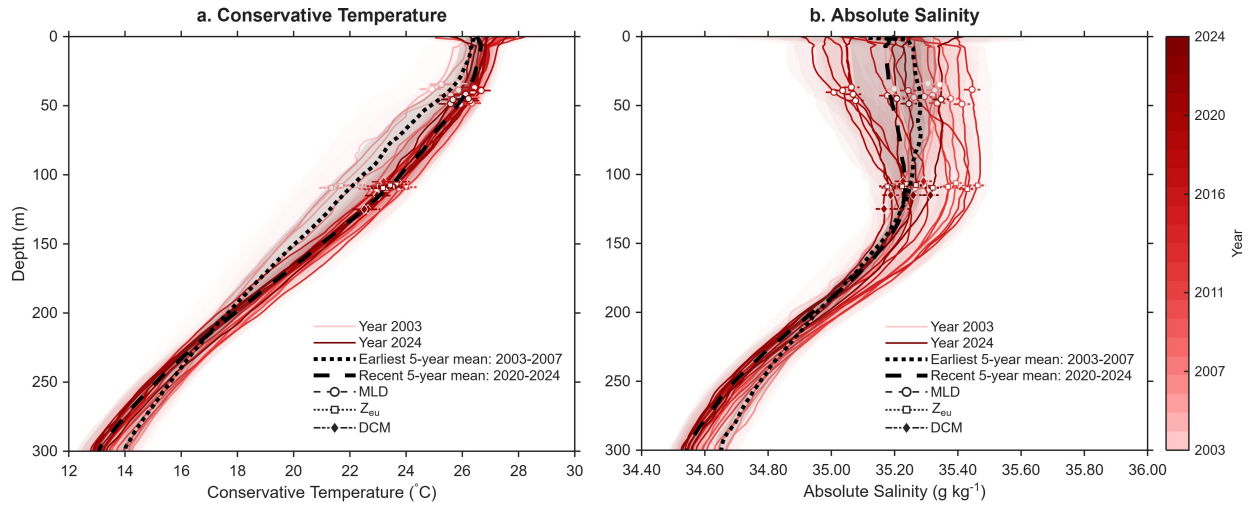


Figure S4. Yearly vertical profiles of Conservative Temperature and Absolute Salinity in the North Pacific Subtropical Gyre (NPSG). (a, b) Annual depth profiles of (a) Conservative Temperature and (b) Absolute Salinity derived from physical Argo observations from 2003 to 2024. Annual profiles were calculated from monthly platform medians, followed by equal-month annual platform means and equal-platform yearly means. Profile colours progress from light to dark red for earlier to more recent years, with light shading indicating the 95% confidence interval (CI). Dotted and dashed black lines show the earliest (2003 to 2007) and recent (2020 to 2024) five-year mean profiles, respectively. Open circles, open squares, and filled diamonds indicate mixed-layer depth (MLD), Z_{eu} , and deep chlorophyll maximum (DCM), respectively.

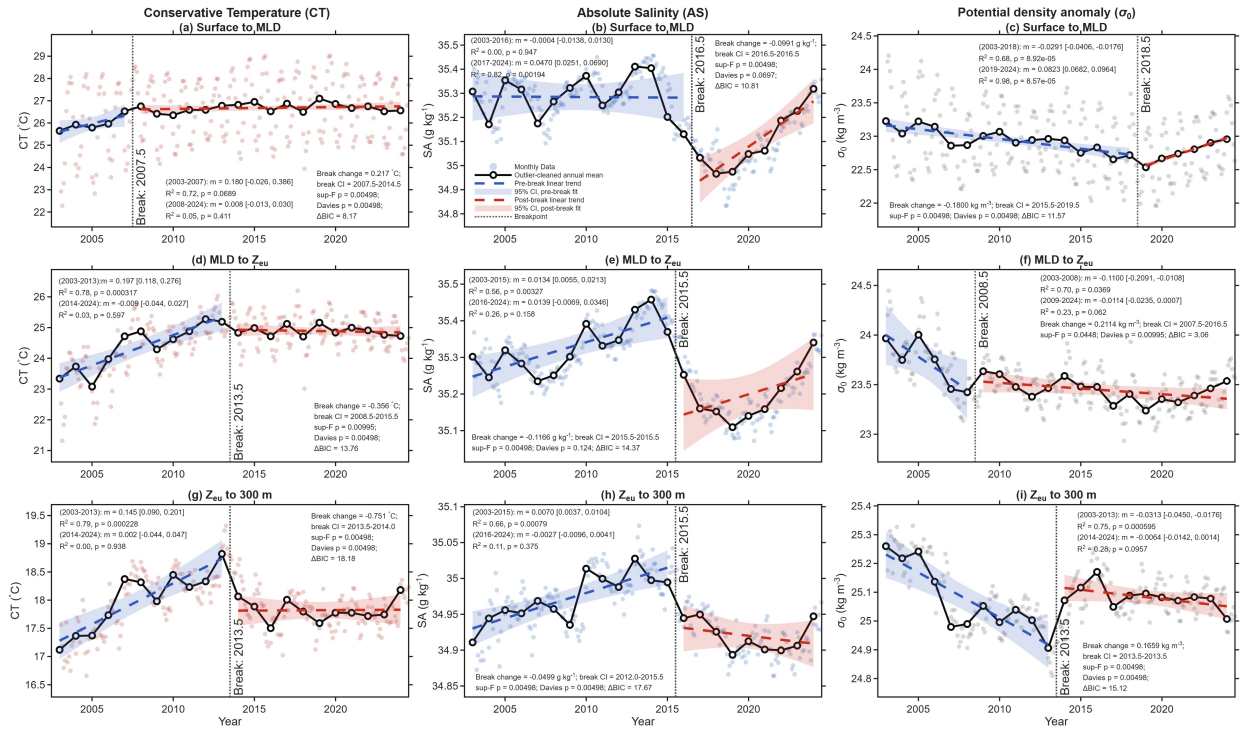


Figure S5. Layer-resolved Conservative Temperature, Absolute Salinity, and potential density anomaly within dynamically defined upper-ocean layers of the North Pacific Subtropical Gyre. Conservative Temperature (CT; left column), Absolute Salinity (SA; middle column), and potential density anomaly (σ_0 ; right column) were evaluated within the same three contemporaneous depth intervals used for the layer-normalized heat-content analysis: **(a-c)** surface to the mixed-layer depth (MLD), **(d-f)** MLD to the euphotic-zone depth (Z_{eu}), and **(g-i)** Z_{eu} to 300 m. All variables were calculated profile-by-profile using the same dynamically varying layer boundaries and depth-cell thickness weighting. Transparent coloured points show monthly layer means, black open circles connected by solid lines show annual means calculated after monthly outlier removal. Blue and red dashed lines show linear trends before and after the selected breakpoint, respectively, with corresponding shaded envelopes indicating the 95% confidence intervals (CI) of the fitted mean trends. The dark dotted vertical line marks the selected breakpoint. Breakpoints were identified using a global one-break minimum-sum-of-squared-errors (SSE) search and evaluated using a Bai-Perron-style bootstrap supremum- F (sup-F) test, continuous segmented regression, a Davies-type bootstrap maximum slope-change test, and model comparison using the Akaike information criterion (AIC), corrected Akaike information criterion (AICc), and Bayesian information criterion (BIC); breakpoint uncertainty was estimated using residual bootstrap resampling. Trend slopes (m), 95% CI, coefficient of determination (R^2), probability value (p -value), and change across the breakpoint are reported in each panel. The layer-resolved comparison illustrates the asynchronous evolution of thermal, haline, and density properties across the upper water column, including earlier thermal changes, later salinity adjustments, and depth-dependent density responses.

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