Text A1. Methodology - additional information

In situ NPP estimates

In situ sampling was conducted in August 2018 and August and December 2019. A standard procedure was followed to generate an in situ estimate of NPP from plastic bottles collected at 10, 20, 40, 60, 90 m and the maximum fluorescence depth. NPP rates were evaluated during in situ incubations by measuring ^{14}C uptake from water samples collected in dark plastic bottles at the same discrete depth. Plastic bottles were stored at 0 – 2°C.

Two subsamples (250 mL) of each depth were placed in a light and a dark polystyrene bottle. Aqueous sodium bicarbonate ($NaH^{14}CO_3$) was added to these polystyrene bottles at a final concentration of $0.1\,mCi\,mL^{-1}$. From each polystyrene bottle, two subsamples ($250\,\mu L$) were taken and fixed with pure $250\,\mu L$ ethanolamine to determine the added carbon concentrations.

The polystyrene bottles were then deployed at the corresponding sampled depths, using a freely drifting mooring rig, either free-floating or tethered to an ice floe. The bottles were retrieved after 18 – 24 h, and their contents were filtered into 25 mmGF/F filters using low-pressure vacuum. Subsequently, the filters were placed in 20 mL scintillation vials, and $750\,\mu L$ concentrated hydrochloric acid (HCl) was added to remove unincorporated inorganic carbon. Then 10 mL of the scintillation cocktail (Ecolume) was added to the samples, which were immediately analysed on a scintillation counter. Further details on methodologies can be found in The Nansen Legacy methods documents (The Nansen Legacy, 2022).

Remote sensing data

Daily SIC data (1980 – 2021) were derived from brightness temperature data sourced from the National Snow and Ice Data Center (NSIDC) and processed with the Passive Microwave Boostrap-v3 algorithm Comiso (2017). These data are gridded on a polar stereographic projection with 25×25 km spatial resolution. The error estimates range 15 — 20% near the Arctic ice margin and in seasonally ice-covered regions (Cavalieri et al., 1991; Comiso and Kwok, 1996; Comiso et al., 1997, 2017), and there is a 20% underestimation during the period of low sea ice concentration relative to ship-based observations (Spreen et al., 2008; Kern et al., 2020). Therefore, the open water area and the number of open water days are potentially overestimated.

Daily Chl-a concentration data (2002 – 2021) were derived from ocean colour measurements from the Moderate Resolution Imaging Spectroradiometer sensors on board the Aqua satellite (MODIS-A) using the OCI algorithm (Hu et al., 2012). These data are gridded on a polar stereographic projection with a 4×4 km spatial resolution and a daily temporal resolution (NASA, 2022). Although it is possible to combine data from the first ocean colour sensor, namely the Coastal Zone Colour Scanner (CZCS, 1979–1986), with data from more recent (1998– ongoing) and modern sensors (Oziel et al., 2022) changes in Arctic phytoplankton NPP and Chl-a are often exclusively evaluated using the latter (e.g., Lewis et al., 2020).

TOPAZ model

TOPAZ refers to the state-of-the-art coupled ocean and marine ecosystem model TOPAZ5-ECOSMO. TOPAZ is a sea ice and ocean data assimilation forecast system for the North Atlantic and Arctic Ocean north of 62°N (Sakov et al., 2012). TOPAZ is a state-of-the-art coupled ocean and marine ecosystem model that uses weekly assimilation of observations available in near real time from in situ profilers and remote sensing data on SIC, iceH, sea surface temperature, sea level height and surface Chl-a concentration (Sakov et al., 2012). The surface Chl-a concentration is projected downward assuming a Gaussian function (Uitz et al., 2006).

In this paper, TOPAZ output refers to the physical and biological reanalysis output between 2019 and 2021. There are different grids for the biological and physical variables. The biological output (e.g., NPP) is gridded on a stereographic projection with a spatial resolution of $6.25 \times 6.25\,\mathrm{km}$ at the north pole and 40 fixed vertical levels on the z-coordinate. The physical output (e.g., SIC) is gridded on a polar stereographic projection $12.25 \times 12.25\,\mathrm{km}$ at the north pole and 20 vertical levels. The depth coordinates alternate between fix depths in the unstratified mixed layer (z coordinate) and varying depths in the stratified ocean (isopycnal coordinates). The biological and physical components of TOPAZ have been described and thoroughly evaluated in previous work (Schrum et al., 2006; Sakov et al., 2012; Daewel and Schrum, 2013; Yumruktepe et al., 2022).

From TOPAZ reanalysis we download daily SIC (https://doi.org/10.48670/moi-00001), and daily NPP and Chl-a concentration (Link D in Table 2). One limitation of TOPAZ output is that the physical model does not allow light to penetrate through sea ice, therefore, there is no growth of phytoplankton under sea ice due to limitation of light (Yumruktepe et al., 2022).

BLING model

BLING output (1980 – 2021) refers to the ensemble physical and biological output of numerical simulations using the ocean model Nucleus for European Modelling of the Ocean (NEMO) 3.6 (Madec and the NEMO team, 2008) coupled to the Louvain la-Neauve Ice Model 2 (LIM2) (Vancoppenolle et al., 2009) and the marine biogeochemical model, Biogeochemistry with Light Iron and Nutrient limitation and Gases 0 with Dissolved Inorganic Carbon (BLINGv0DIC) (Galbraith et al., 2010, 2015).

Simulations were carried out in the ANHA4 configuration that includes the Arctic and North Atlantic Ocean north of $20°\mathrm{N}$ with a spatial resolution of 0.25 degrees and 50 vertical levels on a z coordinate system. The spatial resolution of ANHA4 within the northern Barents Sea is approximately $12 \times 12\,\mathrm{km}$. Table 12 lists the details of the simulations used to form the BLING ensemble. Additional information on tidal forcing, rivers, and glacier runoff forcing can be found online (Myers, 2023).

The simulations were initialised from the climatological conditions. For the ocean and ice components, the climatology was derived from the sources listed in Table 12, and for the biological component, we used data from the World Ocean Atlas database (WOA13) and the Global Ocean Data Analysis Project (GLODAP). For the analysis of the upper $100\,\mathrm{m}$ surface ocean, the adjustment period of 1 to 2 years can suffice because the winter mixing layer typically reach this depth. Nevertheless, here one of the simulations was started in 1958; 20 years before the starting year of the analysis (1980).

Fitting a seasonal function

The seasonal function consisted of a standardized seasonal climatology (1980 – 2021) of BLING output. For each grid cell, the BLING model output was first interpolated to the daily mean and smoothed using a running mean with a 10-day window. Second, the seasonal cycle was standardized by the seasonal maximum. This standardized seasonal function was only used on the observed data (remote sensing-derived and in situ data) when the smoothing spline interpolation was inadequate, usually when there were less than 3 days with data before and after the seasonal maximum (e.g., P2, P4, P6, P7, SICE, PICE1). First, we found the observed seasonal maximum and multiplied it by the standardized seasonal function from the closest BLING grid cell. This resulted in a *predicted* seasonal cycle. Second, we relaxed the magnitude of the predicted seasonal cycle towards the individual observations by taking the weighted mean between the predicted and observed daily values (e.g., using a weight of 1 for prediction and 100 for observation).

Supporting Tables

Table 11. Nansen Legacy station location and annual climatology values of NPP and Chl-a. Time and depth (0 – $100\,\mathbf{m}$) integrated NPP ($\mathbf{gC\,m^{-2}\,yr^{-1}}$). Time and depth (0 – $30\,\mathbf{m}$) averaged Ch-a concentration ($\mathbf{mg\,m^{-3}}$).

STN	LON	LAT	VAR	BLING	TOPAZ	SAT	In situ
P1	76.00	31.23	NPP	117.05	48.04	53.13	39.00
			Chl-a	0.61	0.39	0.36	0.44
P2	77.50	34.00	NPP	68.79	20.98	44.86	40.53
			Chl-a	0.48	0.25	0.11	0.39
P3	78.75	34.00	NPP	53.41	14.59	54.55	NaN
			Chl-a	0.42	0.25	0.13	NaN
P4	79.75	34.00	NPP	49.69	19.82	28.09	63.83
			Chl-a	0.42	0.21	0.32	1.16
P5	80.50	34.01	NPP	42.98	12.47	12.24	22.06
			Chl-a	0.40	0.19	0.05	1.23
P6	81.59	31.52	NPP	34.15	3.45	27.86	7.79
			Chl-a	0.34	0.05	0.29	0.71
P7	81.93	29.14	NPP	30.54	2.49	11.83	0.17
			Chl-a	0.31	0.04	0.20	0.57
SICE19	82.00	25.00	NPP	28.37	1.76	15.99	NaN
			Chl-a	0.29	0.03	0.36	0.28
SICE18	83.22	25.87	NPP	24.57	0.01	11.25	NaN
			Chl-a	0.24	0.00	NaN	NaN
PICE	83.35	31.58	NPP	26.27	0.01	8.36	9.57
			Chl-a	0.25	0.00	0.01	0.04

Column headings abbreviations are STN-Station number, VAR-Variables, LON-Longitude in °E, LAT-Latitude in °N, SAT - remote sensing data.

Table 12. Details on the BLING simulations used to form the ensemble. All simulations included the influence of tides, rivers, and glacier runoff.

Simulation name code	**Period**	**Atmospheric forcing**	**Boundary conditions**	**Initial conditions**
EPM111	1980–2009	CORE2-IA[a] and NCEP[b]	KIEL_K3415[d]	1958 GLORYS2V3[e]
EPM017	1980–2011	CORE2-IA[a]	GLORYS2V3[e]	1980 PHC3[f]
EPM151	2003–2021	CGRF[c]	GLORYS2V3[e]	2002 GLORYS2V3[e]

[a] Coordinated Ocean-ice Reference Experiments phase 2; [b] National Center for Environmental Prediction reanalysis (NCEP); [c] Canadian Meteorological Centre's (CMC) global deterministic prediction system (GDPS) re-forecast (CGRF); [d] Kiel Climate Model System simulation K3415; [e] Global ocean physical reanalysis on a 2-degree horizontal resolution version 3; [f] Polar science center Hydrographic Climatology (PHC) version 3.0

Table 13. Phytoplankton phenology in each subregion. Statistics of the Chl-a bloom parameters in each cluster: median (mean $\pm$ standard deviation), and results of the non-parametric Kruskal Wallis H-test (χ^2), bolded values are significant ($p < 0.05$).

Subregion	**Peak day (DOY[a])**	**Annual mean ($\mathrm{mg\,m^{-3}}$)**	**Seasonality ($\mathrm{mg\,m^{-3}}$)**
Arctic	173 (175 $\pm$ 26)	0.18 (0.18 $\pm$ 0.04)	0.35 (0.17 $\pm$ 0.41)
Subarctic	150 (161 $\pm$ 38)	0.28 (0.30 $\pm$ 0.07)	0.66 (0.77 $\pm$ 0.33)
Atlantic	140 (146 $\pm$ 25)	0.36 (0.38 $\pm$ 0.11)	0.91 (1.00 $\pm$ 0.41)
H-test	$\chi_{22,209} = 28.75$	$\chi_{22,242} = 153.13$	$\chi_{22,242} = 112.82$

[a] DOY is the Day of the Year using julian calendar.

Supporting Figures

Table 14. Primary production required (PPR, $\mathbf{gC\,yr^{-1}}$) to support fishing yields[a] (Y, $\mathbf{metric\,tons\,yr^{-1}}$) in the ICES areas[b] north of $62°\mathbf{N}$. Y was converted to carbon before estimating PPR by assuming a dry-to-wet weight ratio of 0.2 and a carbon-to-dry weight ratio of 0.45 (Jørgensen et al., 1991).

Species	**Y**	**Trophic level**	**PPR**
Cod (*Gadus morhua*)	400 000	4.1	4.5×10^{13}
Haddock (*Melanogrammus aeglefinus*)	100 000	4.0	9.0×10^{12}
Saithe (*Polliachus virens*)	200 000	4.3	3.6×10^{13}

[a] Y values are from (Fiskeridirektoratet, 2021). [b] PPR estimates used Y for an area that is approximately 3–4× larger than NW-BS. It includes part of ICES areas I, IIa, and IIb (Figure 1.8).

Figure 1.1. NW-BS averaged percentage cover fraction by sea ice and clouds as indicated in the satellite records: monthly mean (red line) and annual mean (black dot).

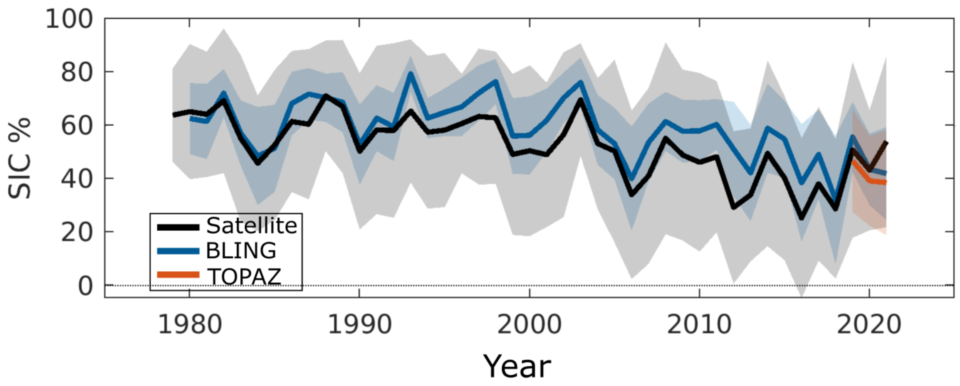

Figure 1.2. Annual mean sea ice concentration (SIC) as estimated: Remote sensing (black), BLING (blue) and TOPAZ (orange), with associate shade being ± 1 standard deviation).

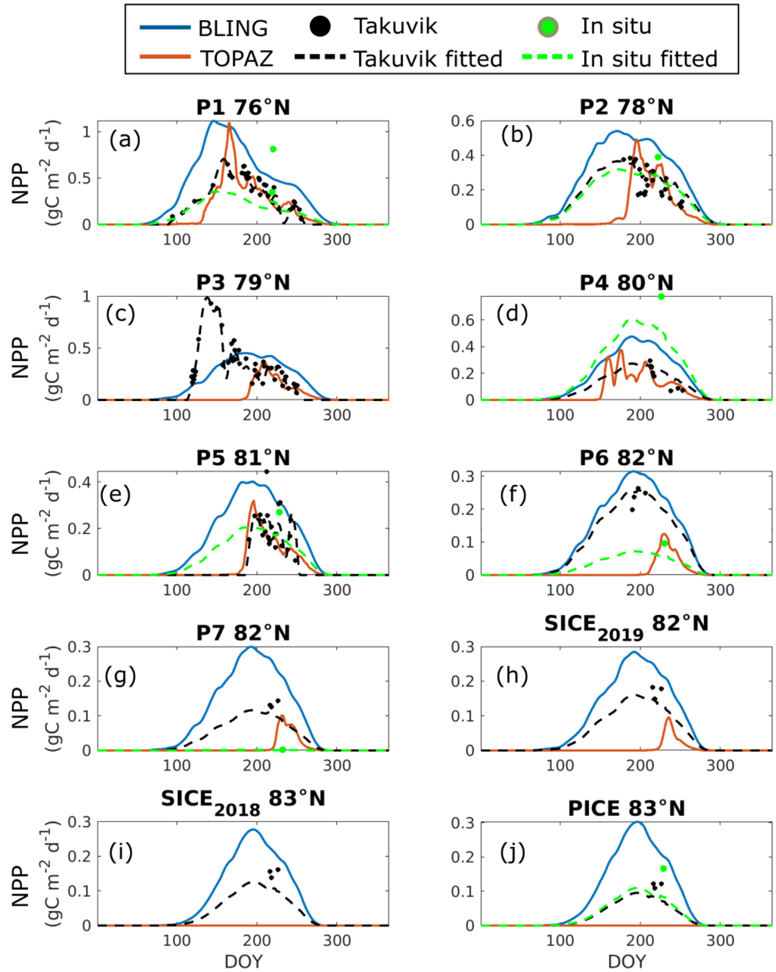

Figure 1.3. Seasonal cycle of net primary production (NPP) at Nansen Legacy stations in Figure 1. Daily depth-integrated (0 – 100 m) NPP at each station against Day of the Year (DOY) as estimated by BLING (solid blue line), TOPAZ (solid orange line), Takuvik (black dots and dashed line), and in situ (green dots and dashed line). Dots are the original data, whereas dashed lines are the extrapolated daily values (see Text A).

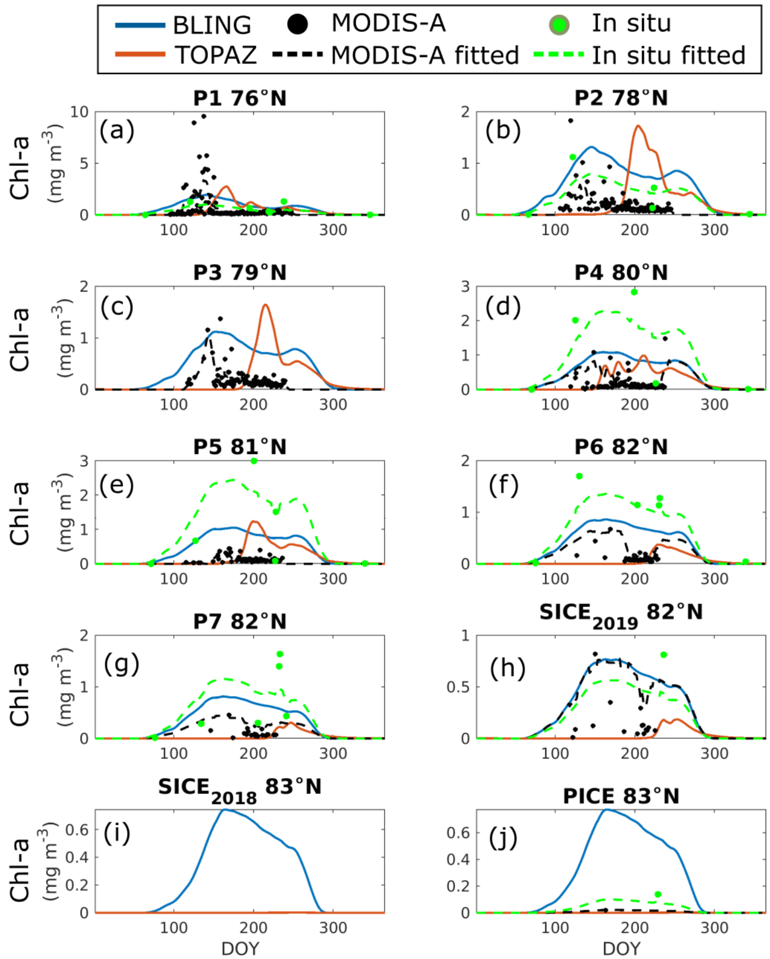

Figure 1.4. The seasonal cycle of Chl-a at Nansen Legacy stations from Figure 1. Daily depth-averaged (0–30 m) Chl-a at each station as estimated by BLING (solid blue line), TOPAZ (solid orange line), Remote sensing (black dots and black dashed line), and in situ (green dots and green dashed line). Dots are all data available for the specific dataset (when a day was available in multiple years, a median Chl-a for that day was plotted). The dashed lines are the extrapolated daily values (see Text A).

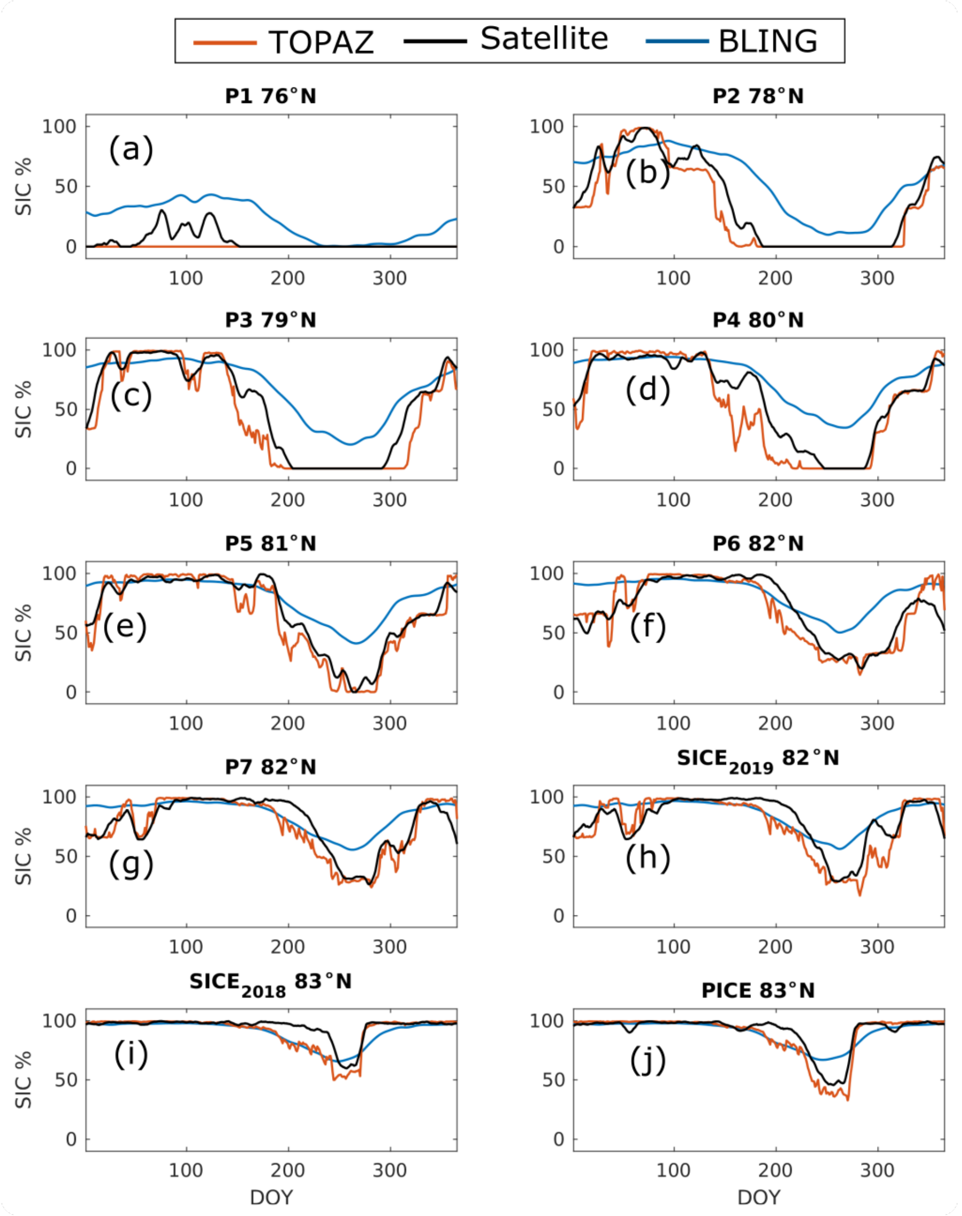

Figure 1.5. The seasonal cycle of SIC at Nansen Legacy stations from Figure 1 as estimated by BLING (solid blue line), TOPAZ (solid orange line), Remote sensing (solid black line).

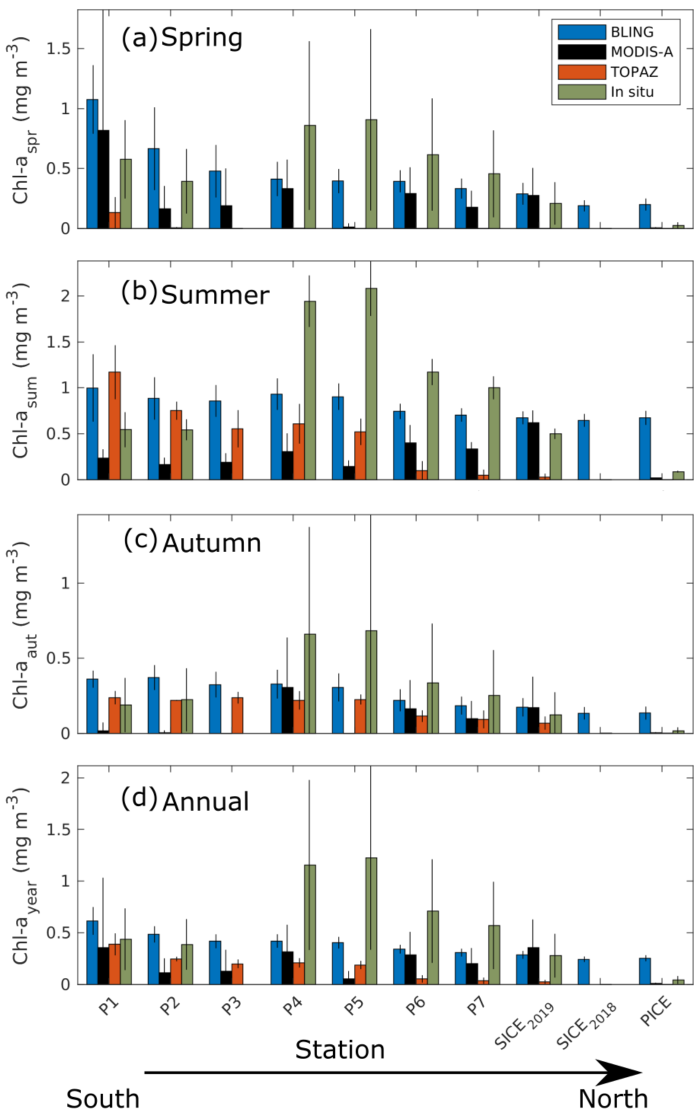

Figure 1.6. Seasonal and annual estimates of averaged Chl-a at each station estimated by BLING (blue), Takuvik or MODIS-A (black), TOPAZ (orange), and in situ (green). Temporal and depth (0 – 30 m) averaged. Periods are (a) spring: March to May, (b) Summer: June to August, (c) Autumn: September to November, and (d) annual: January to December. Standard deviations are included when possible. For in situ and Takuvik the estimates are based on the fitted seasonal cycles (e.g., green lines in Figure 1.4). Note the different ranges in the y-axis on each panel.

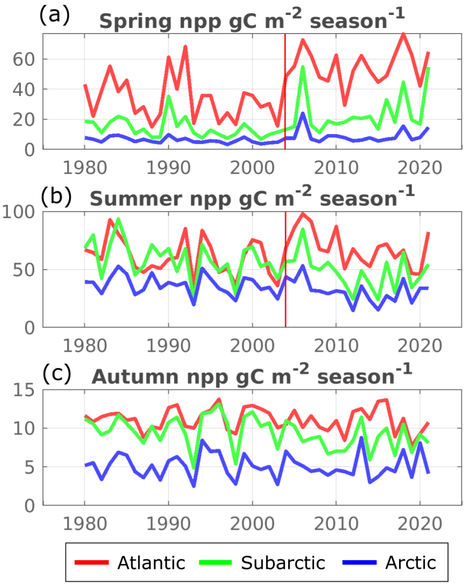

Figure 1.7. Interannual variability in the seasonal estimates of NPP ($\mathrm{gC\,m^{-2}\,season^{-1}}$) using BLING output for each subregion of the NW-BS: Atlantic (red), Subarctic (green), and Arctic (blue). Vertical lines in the panels marked abrupt changes in the NPP time series with the colour identifying the subregion where the change point was detected.

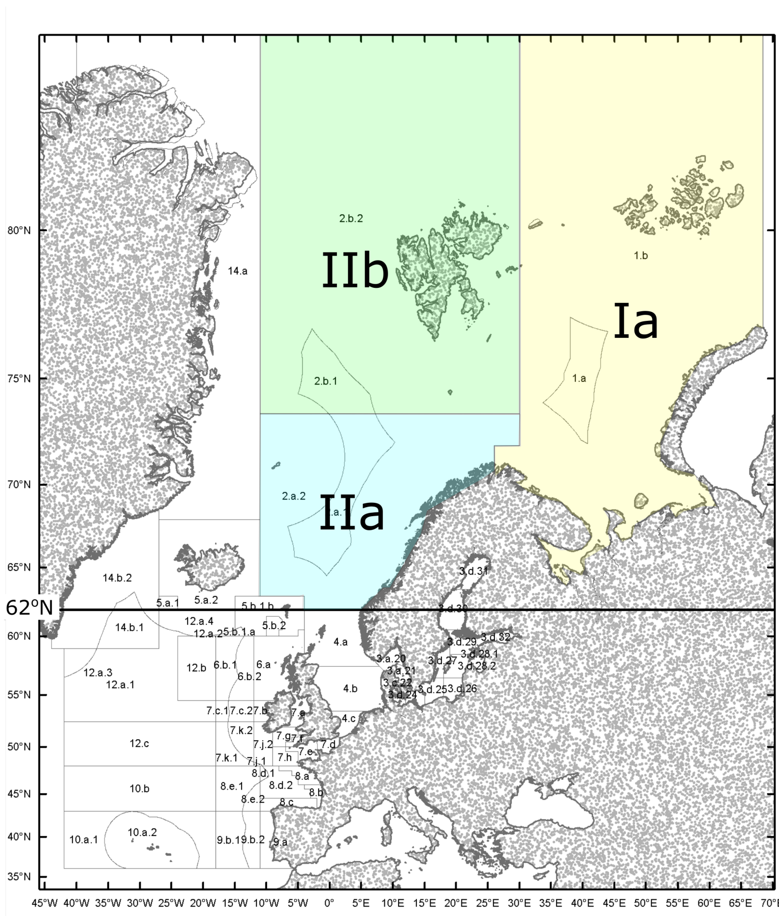

Figure 1.8. International Council for the Exploration of the Sea (ICES) statistical areas relevant to our PPR estimation.Modified from ICES areas full map 2016 (ICES, 2006) to highlight areas north of 62°C: Ia, IIa, IIb.