

Applying Two-Eyed Seeing to Water Monitoring in Pitu'paq (Bras d'Or Lake)

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APPLYING TWO-EYED SEEING TO WATER MONITORING IN PITU'PAQ (BRAS D'OR LAKE)

by

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ABSTRACT

Hardy, M., Denny, S., McIsaac, A., Stephens Elwell, R., Denny, L., Denny, S., Johnson, J.T., Devred, E. 2026. Applying Two-Eyed Seeing to Water Monitoring in Pitu'paq (Bras d'Or Lake). Can. Tech. Rep. Fish. Aquat. Sci. 3811: vi + 36 p. <https://doi.org/10.60825/2mcn-cx25>

Pitu'paq (Bras d'Or Lake) is a complex saltwater estuary designated as a UNESCO Biosphere region. This unique body of water, historically referred to as Pitu'paq by the Mi'kmaw, hosts a rich diversity of people and wildlife, providing terrestrial, marine, and coastal habitats, as well as extensive wetlands, bogs, and barachois ponds. The present document summarises the seasonal variation of the aquatic ecosystem's physical and biogeochemical properties of the lake recorded by combining *in situ* and satellite measurements at selected locations between 2022 and 2024. The data collections and project objective to learn about the physical and biological status of Pitu'paq guided by Mi'kmaq principles: Netukulimk and Etuaptmumk (Two-Eyed Seeing). The technical report summarizes the data collected during the 3-year time span of the project.

RÉSUMÉ

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Pitu'paq (lac Bras d'Or) est un estuaire d'eau salée complexe désigné comme réserve de biosphère par l'UNESCO. Ce plan d'eau unique, historiquement appelé Pitu'paq par les Mi'kmaq, abrite une grande diversité de populations humaines et d'espèces sauvages, offrant des habitats terrestres, marins et côtiers, ainsi que de vastes zones humides, des tourbières et des étangs de barachois. Le présent document résume les variations saisonnières des propriétés physiques et biogéochimiques de l'écosystème aquatique du lac, échantillonnées grâce à la combinaison de mesures in situ et satellitaires effectuées à des emplacements sélectionnés entre 2022 et 2024. La collecte des données et l'objectif du projet visaient à mieux comprendre l'état physique et biologique du lac Pitu'paq, en s'inspirant des principes Mi'kmaq : Netukulimk et Etuaptmumk (approche à double perspective). Le rapport technique résume les données recueillies au cours des trois années qu'a duré le projet.

1 Introduction

The Bras d'Or Lake or Pitu'paq (as referred to herein) is a large and unique saltwater estuary located in the center of Cape Breton Island, Nova Scotia. This unique body of water hosts a rich diversity of people and wildlife by providing terrestrial, marine, and coastal habitats, as well as extensive wetlands, bogs, and barachois ponds (a term used in Atlantic Canada to refer to a coastal lagoon that is partially or completely closed off from the lake). Cape Breton Island is also referred to as Unama'kik, one of the seven districts that make up Mi'kma'ki, the ancestral and unceded territory of the Mi'kmaq people. There are six Mi'kmaq communities in Unama'kik with five of them situated along the shores of Pitu'paq, this includes We'koqma'q (Whycocomagh), Waqmitkuk (Wagmatcook), We'kistoqnik (Eskasoni), Potlotek (Chapel Island), and Malikewe'jk (Malagawatch) (seasonally occupied). The sixth community in Cape Breton is Maupeltuk (Membertou) which is situated near the Sydney Harbour.

Eskasoni Fish and Wildlife Commission (EFWC) is located in Eskasoni First Nation, the largest Mi'kmaq community in Atlantic Canada. EFWC was established in 1991 and focuses on watershed, habitat, and species protection, along with outreach within the community (<https://efwc.ca/about/who-are-efwc/>). Unama'ki Institute of Natural Resources (UINR), also located in Eskasoni First Nation, was established in 1999 and represents the five Mi'kmaq communities in Unama'ki on natural resource issues. UINR leads best-management practices in Unama'ki by integrating Netukulimk and Etuaptumumk (Two-Eyed Seeing), and maintains many partnerships that contribute to understanding and protecting the ecosystem (<https://www.uinr.ca/about/>).

The oceanography of Pitu'paq has been studied for decades by various organizations and institutions to understand its physical and biogeochemical functioning, assess its health and ability to support higher trophic levels, and determine the potential effects on food security and moderate livelihood fishing. Considerable research has been done on the hydrodynamics of Pitu'paq, (e.g., Krauel 1975; Gurbutt et al. 1993; Petrie and Bugden 2002; Dupont et al. 2003; Yang et al. 2007), as well as the chemical and biological properties (e.g., Geen and Hargrave 1966; Strain et al. 2001; Strain and Yeats 2002; Parker et al. 2007; Drozdowski et al. 2014; Manning et al. 2019; Punshon et al. 2022). But most importantly, traditional knowledge has been at the heart of Pitu'paq management led by UINR, EFWC, and Bras d'Or Collaborative Environmental Planning Initiative (CEPI) (e.g., CEPI 2006; UINR and CEPI 2007).

In 2011, Pitu'paq was designated a UNESCO (United Nations Educational, Scientific, and Cultural Organization) Biosphere and recertified in 2022. Biosphere sites are recognized under UNESCO's Man and the Biosphere (MAB) Programme as ecologically significant regions that promote sustainability and conservation by engaging all community stakeholders and relaying sound science (<https://www.unesco.org/en/mab/bras-dor-lake>). In partnership with UINR, Fisheries and Oceans Canada (DFO) proposed Pitu'paq as a Tier 1 site in its Marine Conservation Network in the Scotian Shelf-Bay of Fundy Bioregion for representation as a unique inland estuarine ecosystem. Tier 1 sites are a high priority for implementation due to their ecological characteristics and/or feasibility considerations, including interest from rightsholders, other levels of government, marine users, and stakeholders. Despite its ecological significance and the increasing anthropogenic pressures on Pitu'paq, including real estate development along the shoreline and increases in tourism and recreational usage, no broadscale assessment of the water quality conditions have been conducted in recent years to assess the health of Pitu'paq.

In 2021, UINR, EFWC, and DFO Maritimes region science co-developed a project to inform on the status of Pitu'paq following Etuaptumumk principles to guide research questions and a sampling strategy that would form the basis of long-term monitoring program following a previous initiative from DFO (Drozdowski et al. 2014). Funded by DFO's Marine Conservation Targets (MCT) program, an oceanographic monitoring framework was established and implemented from 2022 to 2024 in collaboration with both EFWC and UINR. *In situ* water sampling and data collection was planned to occur on a monthly frequency at up to 11 stations. In addition to *in situ* sampling, satellite remote sensing was used as a non-invasive tool for monitoring and quantifying spatio-temporal changes at both seasonal and inter-annual scales. Using over 20 years of satellite measurements will allow us to establish baseline conditions and quantify changes that may have occurred in an area lacking routine environmental monitoring and relate these findings to those documented through Mi'kmaq Ecological Knowledge (MEK). Western science can aid in addressing gaps in traditional knowledge by quantifying observations made by local communities, such as changes in the magnitude and seasonal cycle of water transparency and how it affects primary production, sediment loading and discharge, and the impacts of shoreline erosion on the ecosystem. To our knowledge, satellite observations and ocean color have not been extensively applied in Pitu'paq, and the current study addresses this gap.

2 Methods

2.1 Study area and sampling frequency

The present study focuses on Pitu'paq within an area bounded by -60.3 to -61.3 °W and 45.6 to 46.3 °N where 11 stations were selected using Two-Eyed Seeing principles, see Table C.1 and Figure D.1 for the locations of stations sampled. Table C.2 shows the sampling frequency at each station between 2022 and 2024. Out of the 11 stations selected, the AZMPDeep and AZMPWhy were included given that they have been sampled between 2009 and 2012 through a collaboration between DFO, Cape Breton University (CBU), and UINR and were considered as possible additions to the Atlantic Zone Monitoring Program (AZMP) (Mitchell et al. 2002). An additional two open water sites, named BigB and BenEoin, were selected for satellite data match up and to provide information on some of the deeper areas of Pitu'paq. The remaining sites were selected based on previously sampled locations by EFWC (collection of water samples for chlorophyll-a concentration analysis) and proximity to one of the five Mi'kmaq communities located around Pitu'paq. The initial goal of the project was to sample on a monthly basis but challenging weather (e.g., ice and snow in winter, storm and hurricanes in Fall) and staff availability prevented fieldwork for several months (see Table C.1 for a detailed number of stations sampled per month).

2.2 Methodology

2.2.1 CTD and *in situ* data collection

Sample collection and processing followed established standard protocols to maintain consistency with AZMP (Mitchell et al. 2002). At each station, a CTD (conductivity, temperature and depth) profile was first collected before the deployment of 4 L Niskin bottles to collect water at select depths based on station bathymetry (see Table C.1 for depths sampled at each station). The *Uncle Simon* vessel provided by EFWC was mainly used to sample the sites of interest, and the DFO science vessel *PackCat* was used when the *Uncle Simon* was unavailable.

Sampling from the *Uncle Simon* involved manually deploying a SeaBird Electronics SBE 25plus Sealogger CTD package using a marked rope and Niskin bottles were manually closed using messengers. On the *PackCat*, a SBE 19plus CTD installed in a SBE 55 ECO water sampler rosette equipped with an auto-fire module (AFM) was used for integrated CTD and water sample collection at pre-programmed depths. Both CTD systems were equipped with additional sensors to measure oxygen and chlorophyll-a fluorescence. Standard operating procedures involved deploying the CTDs over the side of the vessel and held submerged at the surface for 3 minutes to allow the pump systems to turn on and the sensors to stabilize. Following this, the CTD was lowered to the desired depth, typically 3-5 m above bottom or up to 60 m deep at the deepest stations.

When Niskin bottles were returned on deck, water from each depth was collected in Nalgene bottles (covered in duct tape to reduce light exposure). The bottles were subsequently stored in a cooler away from natural light until processed at EFWC within a couple hours. Preserved samples were appropriately stored at EFWC until transport back to the Bedford Institute of Oceanography (BIO) where the samples were processed and laboratory analyses were performed. Transport of preserved samples occurred in an ice-filled cooler or liquid nitrogen filled dry shipper, depending on their nature.

For all depths, water samples were collected to measure nutrients ($\mu\text{mol L}^{-1}$), Turner-derived chlorophyll-a concentration (chl-a_T , $\text{mg}\cdot\text{m}^{-3}$), HPLC phytoplankton pigments ($\text{mg}\cdot\text{m}^{-3}$), flow cytometry-derived phytoplankton and bacteria abundance ($\#\text{cell}\cdot\text{L}^{-1}$), and coloured dissolved organic matter (a_{CDOM} , m^{-1}). Water samples at the surface were also collected to measure phytoplankton and detritus absorption coefficients (a_{phy} and a_{det} respectively, m^{-1}) and particulate organic carbon and nitrogen concentration (POC and PON respectively, $\text{mg}\cdot\text{m}^{-3}$). When time and weather permitted, radiometric measurements were collected at deep stations away from the coast including: total solar spectral irradiance incident on the water surface (E_s , $\text{W}\cdot\text{m}^{-2}$), downwelling irradiance (E_d , $\text{W}\cdot\text{m}^{-2}$) and upwelling radiance (L_u , $\text{W}\cdot\text{m}^{-2}\cdot\text{sr}^{-1}$) at wavelengths between 350 and 750 nm. The collection and laboratory processing methods applied for each parameter are detailed in the sections below.

2.2.2 Nutrients

Nutrient samples were collected in duplicate in 10 mL plastic tubes that had been rinsed 3 times with sample water and filled near the top (leaving room for water expansion after freezing), and

stored at -20 °C. Nutrients are highly sensitive to contamination (in particular ammonia), so extra care was taken when handling tubes to avoid contact of the inside of caps and edge of the tube. Samples were analyzed for nitrate (measured as $\text{NO}_2 + \text{NO}_3$), nitrite, ammonium, phosphate and silicate concentration at the BIO using the colorimetry technique on a Seal Analytical continuous-flow Auto-Analyzer 3 (AA3) following international protocols (Mitchell et al. 2002; Becker et al. 2019). A six-point calibration curve was performed at the beginning of every analytical run, while consistency in the measurements was tracked using a certified reference material (CRM; KANSO, Japan) in agreement with recommendation from the repeat hydrography programs GO-SHIP (CLIVAR) and GEOTRACES.

2.2.3 Fluorometric measurements of chlorophyll-a concentration

Turner chlorophyll-a concentration (chl-a_T) in samples was measured using the fluorometric method (Turner 1964; Holm-Hansen et al. 1965). Following the vacuum filtration (8-10 psi) of 100 mL of water on a 25 mm Grade F Glass Fibre (GF/F) filter (mesh of 0.2 micron), the filters were then placed in a scintillation vial filled with 10 mL of 90% acetone. Duplicates were collected for each depth. The vials were left for at least 24 hours in a -20 °C freezer before analyzing to allow pigments to extract into acetone.

The acidification method was used to determine chl-a_T and phaeopigment concentration using an analog Turner-Design 10-AU benchtop fluorometer. The pigment-infused acetone was placed in a quartz cuvette and a before-acid reading in raw fluorescence units was collected. Following this, a few droplets of 10% hydrochloric acid were added to the cuvette and a second measurement was recorded to derive phaeopigment concentration, a degradation product of the chlorophyll-a pigment. Fluorometric counts were converted into concentration using a calibration curve established for the instrument.

2.2.4 Flow cytometry measurements

Flow cytometry samples were collected by pipetting 1.8 mL of sample water directly into a cryovial and preserving it with 0.2 mL of 10% paraformaldehyde. Duplicates were collected for each depth. Cryovials were briefly vortexed and left out for 7 to 8 minutes for the preservative to take effect before being temporarily stored in a liquid nitrogen dryshipper until transported to a -80 °C freezer for storage at BIO.

Samples for measurement of bacteria abundance were prepared by defrosting preserved sample cryovials in a 37 °C water bath for approximately 4 minutes. Flow tubes were prepared with 450 μL TE (Tris-EDTA) buffer, 5 μL SYBR Green I, 5 μL Yellow Green (YG) 1 μm beads, and 50 μL sample water. The prepared flow tubes were then placed in the dark for 10 minutes. Samples were run for three minutes at a medium flow rate (40-60 $\mu\text{L}/\text{min}$) on a Becton Dickinson FACsLyric flow cytometer. Measurements of phytoplankton abundance were performed in a similar manner, flow tubes were prepared with 5 μL YG 1 μm -beads and 1500 μL sample water. The prepared flow tubes were then placed in a dark area to preserve the integrity of the sample until processing on the flow cytometer. The samples were run for 7 minutes at a high flow rate (100-130 $\mu\text{L}/\text{min}$) on the Becton Dickinson FACsLyric flow cytometer. In brief,

cells pass one at a time through a flow cell using hydrodynamic focusing, where they are illuminated by a multiple colored lasers. Detectors measure the fluorescence and scattering properties to help determine phytoplankton taxonomic composition and abundance. Abundances ($\text{cell}\cdot\text{mL}^{-1}$) of four phytoplankton groups (cell size $< 10\ \mu\text{m}$) were determined based on their scattering and fluorescing properties (Li 1994; Aebischer et al. 2017), namely prokaryotes (mainly *synechococcus* spp.), pico-eukaryotes ($< 2\ \mu\text{m}$), ultranano-eukaryotes (including small diatoms with size between 2 and $10\ \mu\text{m}$) and cryptophytes.

2.2.5 Phytoplankton pigments

Samples for phytoplankton pigments analysis were collected by vacuum filtering water (typically 300 mL) and visually inspecting the filter for color on the 25 mm GF/F filter (0.2 micron) to ensure enough material was collected. The filter was placed in a cryovial and temporarily stored in a dryshipper charged with liquid nitrogen until transported to a $-80\ ^\circ\text{C}$ freezer for storage at BIO.

Phytoplankton pigment concentrations were measured using the High Performance Liquid Chromatography (HPLC) method on an Agilent 1200 system as described in Head and Horne (1993) and Stuart et al. (2005). Frozen filters were placed in 95% acetone-filled glass tube, sonicated for about 20 seconds and centrifuged for 2 minutes at 13,000 rpm. The supernatants (150 μL) were placed in a buffer (300 μL), loaded into an autosampler and ran overnight on a C18 column. A gradient of solvents was applied to the column and pigments were identified according to their retention time. The resulting chromatograph provided pigment absorption at selected wavelengths, which was converted into pigment concentration ($\text{mg}\cdot\text{m}^{-3}$) using known concentration of pigment and their associated absorption (i.e., six point calibration curve).

This method allowed the identification of 21 pigments and the determination of their concentration ($\text{mg}\cdot\text{m}^{-3}$): chlorophyll-a (Chl-a), chlorophyll-b (CHL-B), chlorophyll-c1,2 (CHL-C1,2), chlorophyll-c3 (CHL-C3), peridinin (PERID), 19'-butanoyloxyfucoxanthin (19BUT), 19'-hexanoyloxyfucoxanthin (19HEX), fucoxanthin (FUCO), prasinoxanthin (PRASINO), violaxanthin (VIOLA), astaxanthin (ASTAX), diadinoxanthin (DIADIN), diatoxanthin (DIATOX), alloxanthin (ALLOX), zeaxanthin (ZEA), α -carotene (α -CARO), β -carotene (β -CARO) and chlorophyll-a derivative such as chlorophyllide-a, allomer, epimer and phaeopigments.

2.2.6 Phytoplankton, detritus, and colored dissolved organic matter (CDOM) absorption

Samples for phytoplankton ($a_{\text{PHY}}\ (\text{m}^{-1})$) and NAP absorption (detritus, $a_{\text{NAP}}\ (\text{m}^{-1})$) were collected in the same manner as phytoplankton pigments (see section 2.2.5). Analyses were performed on a UV-Vis Shimadzu 2600 spectrometer using the method of Mitchell and Kiefer (1984) as updated by Hoepffner and Sathyendranath (1991) and Kyewalyanga et al. (1997). First the total particulate absorbance of the filter is measured, then the filter was soaked in 20 mL of hot methanol ($60\ ^\circ\text{C}$) to extract pigments followed by vacuum filtering 10 mL of filtered seawater through the filter, and the absorbance of the filter is measured again to obtain $a_{\text{NAP}}\ (\text{m}^{-1})$ (as in Kishino et al. (1985)). Absorbance coefficients were measured at 1-nm intervals from 350-750 nm but only the visible parts of the spectrum is used (400-500 nm). Absorbance was then converted to absorption using the path length correction from Stramski et al. (2015). $a_{\text{PHY}}\ (\text{m}^{-1})$)

is obtained by subtracting a_{NAP} (m^{-1}) from the total particulate absorption. Additional quality checks were performed as outlined in Wilson et al. (2026).

Samples for CDOM absorption (a_{CDOM} (m^{-1})) were prepared by vacuum filtering (8-10 psi) 200-250 mL of sample water through a 47 mm polycarbonate membrane filter (0.2 μm mesh). The filtered sample water is stored in prepared amber bottle that have been acid washed and baked overnight at 450 °C to remove organic matter. Samples are placed in a dark fridge at 4 °C. Sample analysis is performed within three months of collection on a flow cell ultrathin spectrophotometer with a 10 cm pathlength (due to the high load of CDOM in Pitu'paq). Absorbance was measured at 2-nm intervals from 250 to 750 nm and converted to absorption using the following equation:

$$a_{\text{CDOM}}(\lambda) = 2.303 \times A(\lambda)/l \quad (1)$$

where l corresponds to the pathlength ($l = 0.1 \text{ m}$), A corresponds to the absorbance at wavelength λ (nm) and a_{CDOM} represents the absorption coefficient of CDOM (m^{-1}) at λ .

2.2.7 Particulate organic carbon and nitrogen

Samples for particulate organic carbon (POC) and nitrogen (PON) were filtered on pre-baked 25mm GF/F filters (0.2 μm). Filters were baked at 450 °C for overnight (12 hours) to remove all organic material before filtration. Similarly to pigments and absorption samples, 300 mL of water was vacuum filtered to ensure visual color and that enough material was retained for analysis. Duplicates were collected and both filters were folded using tweezers and placed into a single petri dish then stored at -20 °C until analysis in the laboratory at BIO.

POC and PON mass were measured on a CHN elemental Auto-Analyser (Collos 2002) and concentration was determined by dividing the mass by the volume filtered. Several blanks were run at each beginning of a batch of samples, including two air blanks, a cap blank and a filter blank, as well as two standards.

2.2.8 Radiometric measurements

When time and weather permitted, a free-falling HyperPro profiling system consisting of three HyperOCR hyperspectral radiometers and a profiling frame was deployed at deep stations away from coastal areas to measure downwelling irradiance (E_d , W.m^{-2}) and upwelling radiance (L_u , $\text{W.m}^{-2}.\text{sr}^{-1}$) between 350 and 750 nm. Above water irradiance (E_s , W.m^{-2}) using a sensor mounted on the boat was also collected for calibration purposes. These quantities were used to derive remote sensing reflectance, $R_{\text{rs}}(\lambda)$ (sr^{-1}), which is the same quantity measured by ocean colour satellites, and the diffuse attenuation coefficient, $K_d(\lambda)$ (m^{-1}) which provides information on attenuation of sunlight with depth, with λ corresponding to the wavelengths. The instrument was lowered in the water column until the light level reached zero. Three profiles were collected by stations and the average of the three profiles was used. The software package Satlantic 'SatView' was used to visualize the data in real time and process the measurements from raw data to Level 4 format, including reflectance calculation. Remote sensing reflectance was computed following Chase et al. (2017) with modification to accommodate the free-falling mode.

The Satlantic Hyperspectral Ocean Colour Radiometer (HyperOCR) mounted on a free-falling optical profiler was used to collect light data. The HyperOCR profiler is used in tandem with a radiometer located on the boat, which measures the downwelling solar irradiance. The profile was repeated three times at each station and the average of the three profiles was used. The Satlantic ProSoft data analysis package is used for processing the measurements from raw data to Level 4 format.

2.3 Satellite imagery

2.3.1 MODIS data

MODIS Daily Level-1 data (i.e., not corrected for atmospheric pathlength) over Pitu'paq regions of interest were downloaded for over a 20-year period from January 1st 2003 to December 31st 2024 from the Ocean Biology Processing Group (OBPG) at the National Aeronautic and Space Administration (NASA) website (<https://oceancolor.gsfc.nasa.gov>). Level-1 data were atmospherically corrected using the Sea, Earth, and Atmosphere Data Analysis System (SeaDAS) with a ground resolution of 250m. Note that out of 11 bands in the visible and near-infrared, only 2 bands have a nominal resolution of 250 m (i.e., 659 and 865 nm) and two bands have a resolution of 500 m (i.e., 470 and 555 nm). The remaining bands have a resolution of 1000 m. This necessitated the reprojection of all bands on a consistent 250-m grid, including the thermal bands to derive sea-surface temperature. Processing of Level-1 top-of-atmosphere radiance to Level-2 geophysical products at ground level allows selection of a variety of products, including, diffuse attenuation coefficient, chlorophyll-a concentration and more. Due to the lower resolution of MODIS and unable to capture coastal areas, here we only validate *in situ* measurements and report on SST for the station AZMPDeep.

2.3.2 Landsat data

Daily SST Level-2 Collection-Z images at 60m resolution from LandSat (-5,-7,-8) were downloaded from the United States Geological Survey (USGS) website (<https://earthexplorer.usgs.gov/>). Data spans from 2000 to present and excludes 2011 and 2012 due to issues with the alignment of the swathes. For this report, we focused only on 2022 to 2024 data that spanned the project timeline and, as for the MODIS sensor, we report only on SST.

2.4 Data statistical analysis

Given the spatial distribution of the stations and the irregular sampling frequency, stations were grouped together in some instances (e.g., POC monthly variation) to facilitate interpretation and to summarize broader patterns. In this study, stations were grouped according to two criteria: depth and location. When using bathymetric consideration, stations deeper than 40 m were defined as deep (i.e., AZMPWhy, AZMPDeep, GrandNar, BigB, and BenEoin) and stations shallower than 15 m were defined as shallow (include MacInnisIs, Nyanza, Mala, OuterPot,

InnerPot, and CraneCo). When grouping by location, northern stations included AZMPWhy, BigB, MacInnisIs, Nyanza, and GrandNar, while southern stations consisted of AZMPDeep, OuterPot, InnerPot, CraneCo, BenEoin, and Mala, with the Grand Narrows bridge, representing the northern and southern separation.

Mixed layer depth (MLD) was computed from temperature and salinity data measured from each CTD profile to provide information on the seasonal patterns in water column mixing in Pitu'paq. The first step was to compute potential density sigma as a function of salinity and temperature. Mixed layer depth was computed using the density variation approach, namely, the depth of the mixed layer was defined as the depth where density was 0.08 kg m^{-3} greater than the density at 10 m.

Seasonal SST maps from Landsat data were computed by taking the seasonal mean of daily Landsat images between 2022 and 2024. The seasonal months were categorized as winter (December, January, February), spring (March, April, May), summer (June, July, August), and fall (September, October, November). Daily SST data was also extracted (when available) for AZMPDeep using MODIS data and AZMPWhy using Landsat data to validate *in situ* measurements.

3 Results

3.1 Physical properties

Monthly mean temperature of the surface and upper water column ($< 10 \text{ m}$) averaged from 2022 to 2024 peaked in August and can reach up to $22 \text{ }^{\circ}\text{C}$ while deeper waters ($\geq 30 \text{ m}$) peaked later in the year in September/October (Figure D.2). By December, the water column was well mixed and temperatures homogenous over the entire water column. Salinity varied between 18 and 26 PSU, depending on water mixing and freshwater inputs (Figure D.3). We selected three deep stations in different areas of Pitu'paq to display the variation in temperature and salinity (T-S) in 2023 (Figure D.4) and evaluate mixed layer depth (Figure D.5). The T-S diagram showed significant seasonal variability in the warmer and fresher portions of the distributions, whereas the cooler and higher salinity portions generally show greater overlap among months. AZMPDeep occupied a distinctly fresher and generally cooler T-S range than BigB and GrandNar, with overlap among months at high salinity and low temperature. while BigB and GrandNar were comparable in terms of their overall temperature range, BigB displayed higher salinity throughout the year.

The MLD showed large spatial variation between the southern and northern stations (Figure D.5). At GrandNar and BigB, MLD ranged between 10 and 20 m between April and December, while spring and fall mixing was more intense at AZMPDeep with a MLD reaching greater than 40 m in December. It's likely that the MLD extended deeper in January and February, but no data was collected in these months to support this.

3.2 Biogeochemical properties

It is well known that Pitu'paq is nitrate and phosphate limited (Strain and Yeats 2002). This was confirmed from our measurements, which showed that nitrate and phosphate concentration were depleted year round, except at AZMPWhy (Figures D.6 and D.7). AZMPWhy, located in Whycocomagh Bay, consistently showed signs of high nutrient levels, especially below 20 m. Nutrient levels were notably high below 20 m at AZMPWhy which may be due to freshwater runoff and stagnation due to the slower flush rate of the Whycocomagh Bay (Strain and Yeats 2002). Silicate inputs from rivers may support local blooms of diatoms and are therefore in excess, except in the spring, where they are consumed at all stations (Figure D.8).

Chl- a_T concentration, a proxy for phytoplankton biomass, is tightly related to nutrient availability. Phytoplankton biomass started to increase in spring but remained low, while the highest concentration occurred in late summer/early fall for all stations except MacInnisIs which increased throughout the year and peaked in December (Figure D.9).

In addition to chl- a_T concentration, the pigment composition of phytoplankton is measured to inform on community structure (Kramer and Siegel 2019). We measure an array of pigments (Figure D.10, but only the seven pigments with the highest concentration (relative to chl- a concentration) and relative contribution to total biomass are presented in Figure D.11. Peridinin, a marker pigment for dinoflagellates showed the highest concentration (up to 70% of chl- a) and peaked in the fall up to early winter (Figure D.12). Diadinoxanthin and chlorophyll- $c_{1,2}$ showed the second and third highest relative concentration respectively (Figures D.13 and D.14), and a consistent seasonal variation with peridinin in agreement with their high correlations ($R^2 = 0.69$ and 0.79 respectively, Figure D.10). The fucoxanthin pigment, related to diatoms, showed high temporal and spatial variability (Figure D.15), with highest values occurring in spring (i.e., April) at AZMPWhy, MacInnisIs, and CraneCo while other stations peaked in fall (e.g., OuterPot, InnerPot, and Mala). Finally, chlorophyll- b and β -caroten were higher in spring and summer respectively (Figures D.16 and D.17), with the former indicating the presence of green algae such as euglenoids, and the latter being a photoprotective pigment produced by phytoplankton in high light environments.

While composition and concentration of pigments inform on all broad taxonomic groups present in natural water samples, flow cytometry measurements provide abundance ($\text{cell}\cdot\text{mL}^{-1}$) of the smallest phytoplankton cells (less than $\sim 10\ \mu\text{m}$). Cyanobacteria, small unicell phytoplankton that thrive in nutrient poor, well-lit surface water of lakes and estuaries, were most abundant in June and October at all stations (more than $400,000\ \text{cell}\cdot\text{mL}^{-1}$ at Nyanza) except at the InnerPot station where they reached their maximum in August (Figure D.18 a). Their abundance is much lower at depths below 20 m (Figure D.18 b)). Pico-Eukaryotes are more complex cells than prokaryotes as they possess a nucleus and membrane-bound organelles, and they are less abundant than cyanobacteria in Pitu'paq, except at CraneCo where they exhibited a similar abundance in August in the top 20 m (Figure D.19 a) and showed less seasonality with a peak in abundance that occurred in August (e.g., BenEoin) or September (e.g., Mala). At depths below 20 m, the abundance remained low ($< 20,000\ \text{cell}\cdot\text{mL}^{-1}$) except at AZMPWhy, where it reached an abundance of $40,000\ \text{cell}\cdot\text{mL}^{-1}$ and peaked in August (Figure D.18 b). Finally, nano-eukaryotes, which include small diatoms, peaked in September, in agreement with the fucoxanthin pigment signal, and reached about $10,000$ to $15,000\ \text{cell}\cdot\text{mL}^{-1}$ (Figure D.20).

Particulate organic carbon (POC) informs on the carbon cycle and phytoplankton physiological state as POC to chl-a ratio increases in high light levels and low nutrient environments. Monthly mean of POC increased from April to October and showed low values in December (Figure D.21). The ratio of POC to chl-a showed an inverse relationship, with high values in spring (e.g., April to June) and low values in September (Figure D.22). Particulate organic nitrogen (PON) and PON:chl-a ratio showed the same seasonal pattern as POC and POC:chl-a ratio (Figures D.23 and D.24).

3.3 Bio-optical properties

Information on optical properties of the water column informs on light attenuation and potential productivity, it also helps identify phytoplankton community structure with the support of calibration and assessment of satellite data products, which in turn can be used to observe Pitu'paq with higher spatio-temporal resolution compared to *in situ* sampling. Determining the absorption budget of Pitu'paq is an important step in addressing the bio-optical environment of the water. The absorption coefficient of phytoplankton is modulated by biomass concentration and taxonomic composition (Figure D.25). However, two main features remained constant in all phytoplankton absorption coefficients: a main absorption peak at 443 nm and a secondary one around 670 nm due to chl-a absorption. Figure D.25 shows absorption coefficient normalized to 443 nm to emphasize the spectral differences of four spectra: a high peridinin to chl-a ratio (0.63) collected at CraneCo station in November 2024 with a chl-a of 2.66 mg.m^{-3} ; a high fucoxanthin to chl-a ratio (0.4) collected at OuterPot station in September 2024 with a chl-a of 1.92 mg.m^{-3} ; a low chl-a biomass of 0.05 mg.m^{-3} collected at Mala in August 2024; and a high chl-a of 12.5 mg.m^{-3} collected at McInnis station in October 2022.

Absorption by coloured dissolved organic matter (CDOM) shows a different spectral variation, with an exponential decrease with increasing wavelength (Figure D.27). CDOM absorption was higher in spring and fall, with a noticeable “bump” between 250 and 300 nm in April in the surface and deep samples, likely due to the release of organic compounds from land during spring melt. CDOM spectral absorption can be summarized by its absorption at a reference wavelength (often 412 nm, $a_{\text{CDOM}(412)}$) and the slope of the exponential decrease (Figure D.28 and D.29). There was a high variability in $a_{\text{CDOM}(412)}$ between stations with deep stations showing lower magnitude than shallow stations close to shore, which are subject to river runoff and resuspension. CDOM absorption increases in spring, decreases in summer and reaches a maximum in September and October, likely a response to storm and water runoff (Figure D.28). The slope of CDOM absorption was highest in April, indicating a land source (Figure D.29), with slope ranges between 0.012 and 0.022 and high variability between stations. In general, deep stations showed a higher degradation slope than coastal stations.

Finally, we also collected radiometric measurements in ideal weather conditions. Figure D.26 shows reflectance data at 1.5 m deep normalized to the reflectance at 500 nm collected in November 2022 at several deep stations. The low reflectance spectra between 400 and 500 nm compared to the 570 nm values are driven by phytoplankton and CDOM absorption while the bump around 680 nm is due to phytoplankton fluorescence. The underwater reflectance will be converted to above water reflectance to compare with satellite measurements.

3.4 Satellite derived sea-surface temperature (SST)

Sea-surface temperature (SST) from the MODIS sensor data was evaluated to provide detailed information on the seasonal cycle of temperature for AZMPDeep (Figure D.30). In general, satellite data showed a good agreement with *in situ* measurements, suggesting that the satellite-based time series of SST can reliably be used to study spatial and temporal variations of surface temperature. Pitu'paq shows a wide range of temperatures from 0 °C in winter to 25 °C in summer (Figure D.30) over the period evaluated. The Landsat images, while not as frequent as those from MODIS ones, provide high resolution (i.e., 60 m ground pixels) SST allowing for observations in small bays, and can resolve small fronts related to surface circulation. Small bays in winter appeared colder than the main basin, likely as they froze, in spring, the northern more shallow part of Pitu'paq warmed faster than the rest of the lake and reached more than 10 °C by the end of the spring. The lake continued to warm up to reach its maximum temperatures in Fall (Figure D.32).

4 Discussion

Our evaluation of *in situ* water sampling observations collected between 2022 and 2024 and satellite-derived SST measurements demonstrated that Pitu'paq is a spatially heterogeneous and strongly seasonal estuarine system. Pitu'paq's seasonal cycle of physical and biogeochemical properties differs substantially from that of the surrounding ocean, as connections to the Northwest Atlantic are limited to three narrow channels: two in the north (Great Bras d'Or Channel and Little Bras d'Or Channel) and one in the south (Saint Peter's Canal; seasonally operated). The main water exchange between Pitu'paq and the Northwest Atlantic ocean occurs through the Great Bras d'Or Channel.

Overall, the 2022–2024 *in situ* observations show that Pitu'paq is characterized by strong seasonal stratification, low concentrations of nitrate and phosphate across much of the system, a late-summer and fall increase in phytoplankton biomass, substantial seasonal changes in phytoplankton composition, and strong terrestrial influence on coastal optical conditions. AZMPWhy emerged as a particularly distinct region with elevated nutrient concentrations due potentially to restricted flushing. With the exception of satellite-derived measurements evaluated in this study, the limited temporal window over which *in situ* monitoring was conducted constrained our ability to evaluate long-term trends and environmental change in Pitu'paq. These findings therefore provide an important baseline for longer-term monitoring.

The monitoring framework developed in this study demonstrates the value of Etuaptumuk in determining where, when, and why observations were collected. Scientific measurements can quantify changes in temperature, nutrients, phytoplankton, and water transparency, while Mi'kmaq Ecological Knowledge provides a longer-term, local understanding of environmental change and its consequences for species, harvesting, and community use. The two knowledge systems can be used together to identify meaningful indicators and support management decisions grounded in both ecological measurements and lived relationships within Pitu'paq.

Following the guiding principles of Etuaptumuk, future analyses of this dataset will aim to evaluate the nutrient budget of Pitu'paq and whether it has changed relative to historical

sampling events; characterize the seasonal and spatial variability of phytoplankton biomass and community structure and determine how these changes affect water transparency; and assess the influence of shoreline erosion, runoff, and sediment inputs, including whether some areas are more heavily affected than others. However, sustained in situ monitoring, comparison with historical datasets, and integration with Mi'kmaq Ecological Knowledge will be essential for identifying longer-term changes in the physical and biogeochemical conditions and productivity of the Pitu'paq, and for understanding their implications for ecosystem health and sustainable use. Continued integration of Mi'kmaq Ecological Knowledge will be essential for addressing these questions from the perspective of the Indigenous communities that live in Unama'kik, while enhancing DFO's mandate to protect and conserve aquatic ecosystems.

5 Acknowledgements

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Together, we designed and conducted this study, as a result this project reflects Indigenous knowledge systems and scientific approaches. We are thankful for their trust, guidance, and collaboration, and we remain committed to conducting our research in a manner that respects their sovereignty, knowledge systems, and community priorities.

We would also like to thank Kristen Wilson and Lindsay Beazley (DFO Science) for their review of this report. This document was produced using the [csasdown R package](#) using RStudio version 4.4.2 (R Core Team, 2024).

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APPENDIX A ABBREVIATIONS

A: Absorbance
a: Absorption
BIO: Bedford Institute of Oceanography
CDOM: Coloured Dissolved Organic Matter
CEPI: Collaborative Environmental Planning Initiative
Chl-a: Chlorophyll-a
CTD: Conductivity, Temperature, and Depth
DFO: Department of Fisheries and Oceans
EFWC: Eskasoni Fish and Wildlife Commission
HPLC: High Performance Liquid Chromatography
MLD: Mixed Layer Depth
MODIS: Moderate Resolution Imaging Spectroradiometer
UINR: Unama'ki Institute of Natural Resources
POC: Particulate Organic Carbon
PON: Particulate Organic Nitrogen
SST: Sea Surface Temperature

APPENDIX B TRANSLATIONS

Mi'kmaq - English

Pitu'paq - Flowing into Oneness
Unama'kik (or Unama'ki) - Land of Fog
Malikewe'jk - Triangular piece of land formed by body of water
Etuaptumumk - Two-Eyed Seeing
Netukulimk - To have enough, but not more than enough
Msit No'kamaq - All my relations

APPENDIX C TABLES

Table C.1. Coordinates, station depths, and the water collection depths.

Station	Longitude (°W)	Latitude (°N)	Station Depth (m)	Sample Depths (m)
CraneCo	-60.585	45.954	6.0	1
InnerPot	-60.771	45.708	8.6	1, 5
Nyanza	-60.898	46.069	9.0	1, 5
MacInnisIs	-61.068	45.956	10.0	1, 5
Mala	-60.981	45.915	12.1	1, 5
OuterPot	-60.787	45.728	18.4	1, 5, 10
BenEoin	-60.493	45.960	38.0	1, 5, 10, 30
AZMPWhy	-61.125	45.950	45.0	1, 5, 10, 30
GrandNar	-60.805	45.952	50.2	1, 5, 10, 30
AZMPDeep	-60.850	45.820	151.0	1, 5, 10, 60
BigB	-60.725	46.036	193.0	1, 5, 10, 60

Table C.2. Number of stations sampled monthly during the 3-year period from 2022 to 2024.

Month	2022	2023	2024
Jan	0	0	0
Feb	0	0	0
Mar	0	0	0
Apr	0	11	0
May	0	5	9
Jun	0	11	0
Jul	8	10	4
Aug	8	11	11
Sep	0	5	11
Oct	11	6	0
Nov	0	0	0
Dec	9	0	0

APPENDIX D FIGURES

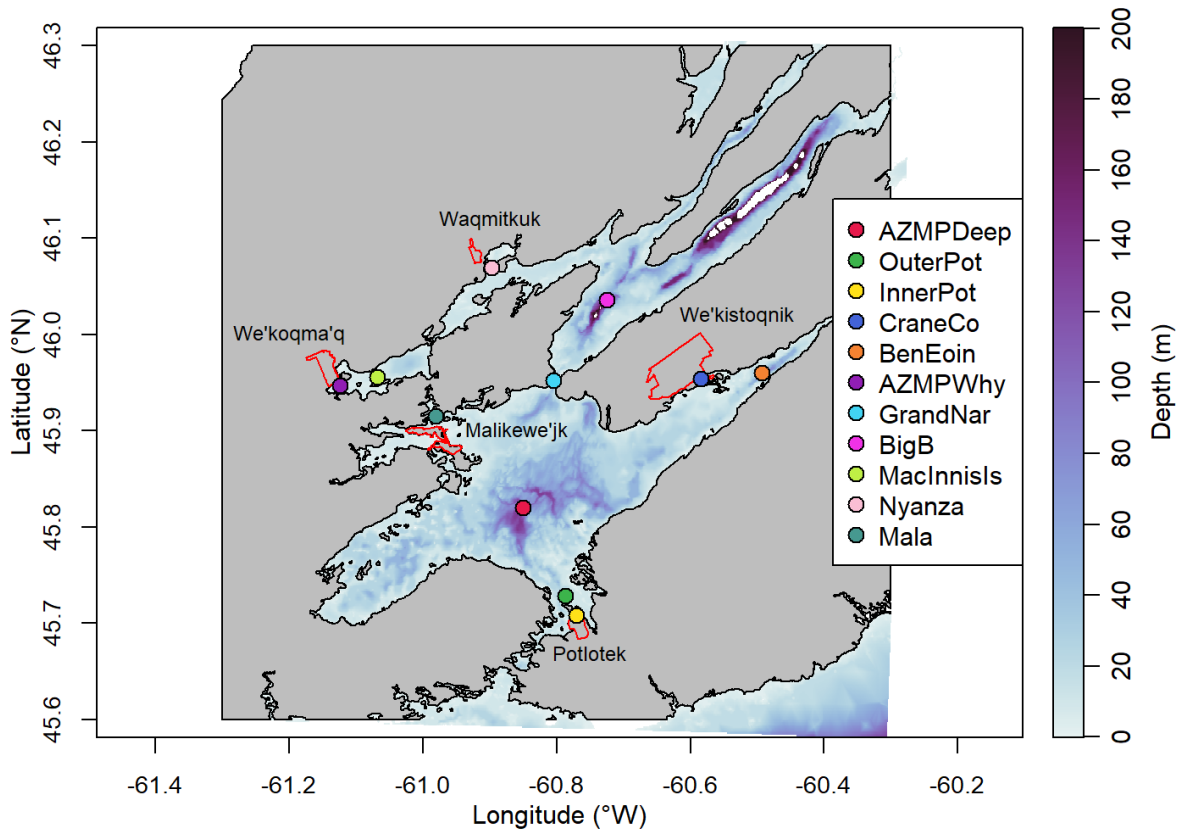


Figure D.1. Bathymetry map of the study area with sampling stations represented by coloured circles. Red bounded areas are the Mi'kmaq communities that reside along Pitu'paq.

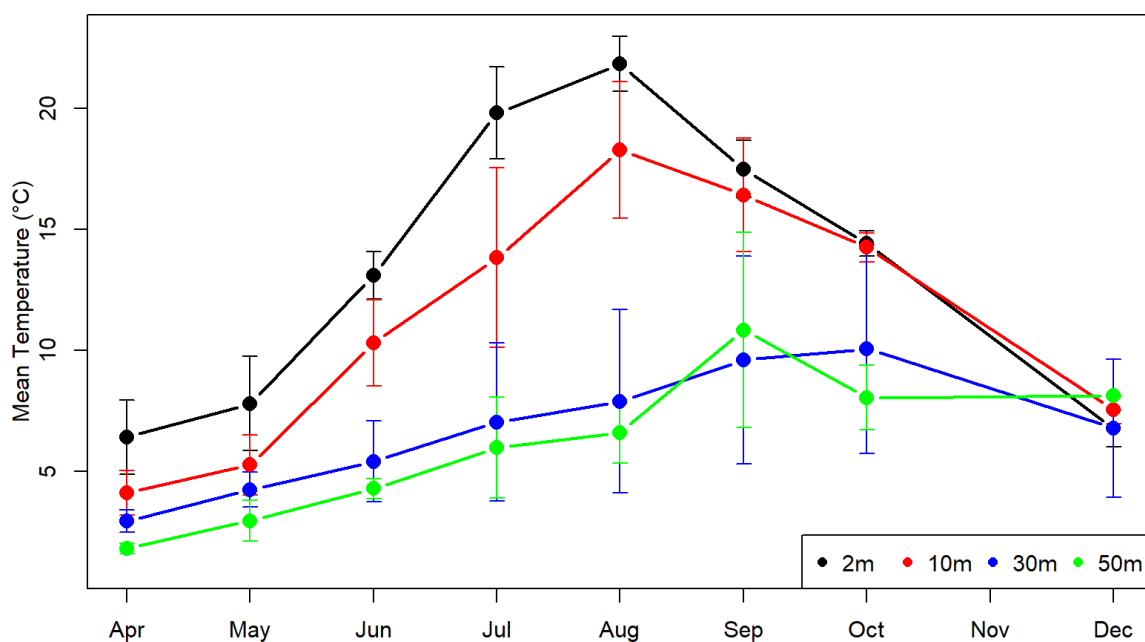


Figure D.2. Monthly mean temperature (°C) including error bars (standard deviation) at 2 m, 10m, 30 m, and 50 m averaged across all stations and years.

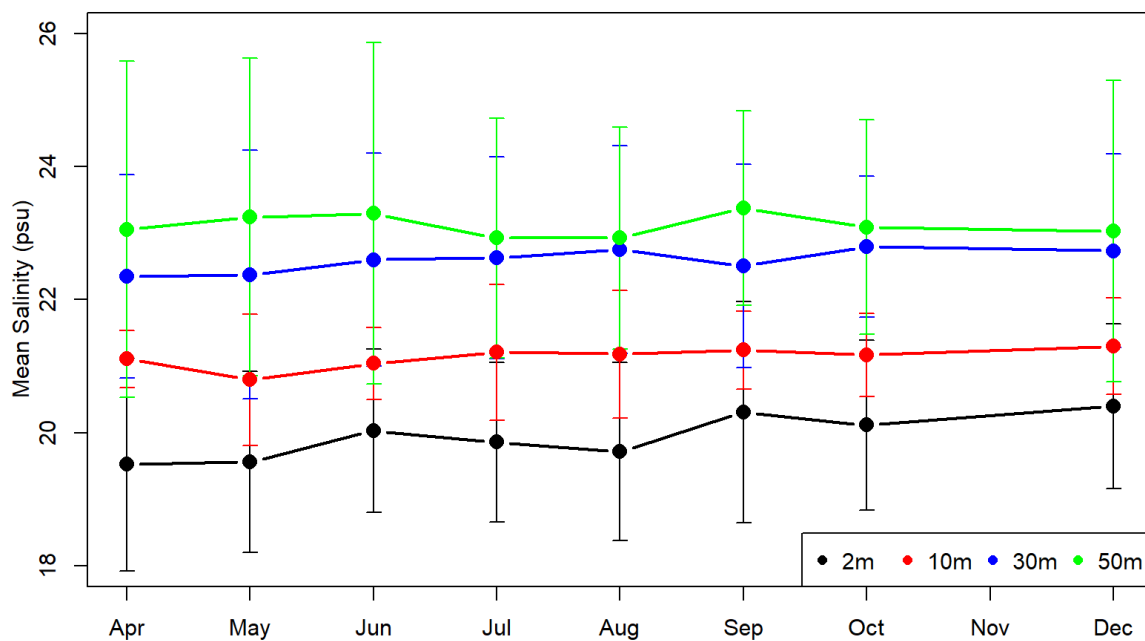


Figure D.3. Monthly mean salinity (psu) including error bars (standard deviation) at 2 m, 10 m, 30 m, and 50 m averaged across all stations and years..

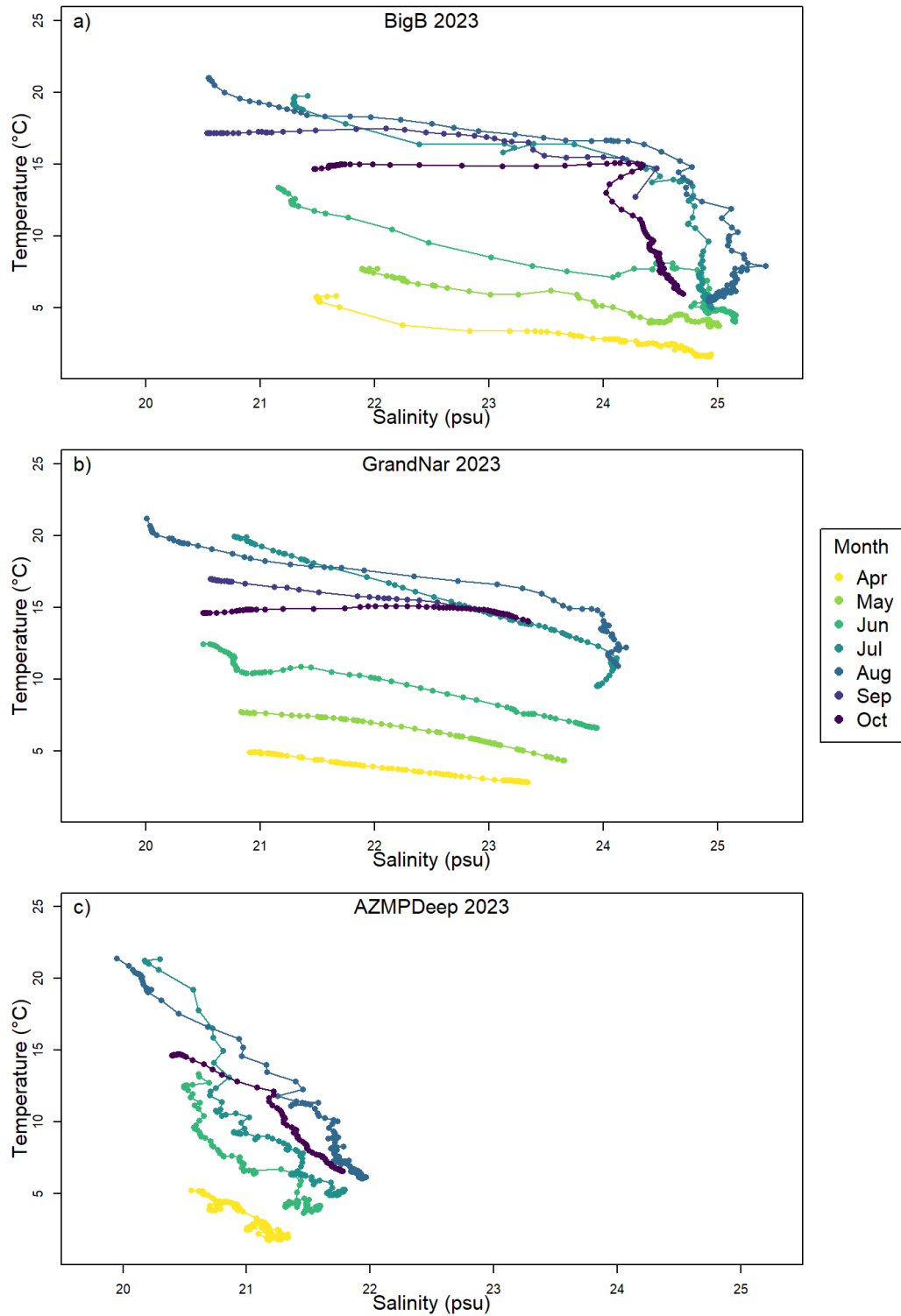


Figure D.4. Temperature versus salinity of three deep stations, a north station (BigB), a south station (AZMPDeep), and the boundary station (GrandNar) for several months in 2023. Includes downcast data from the surface to 60 m.

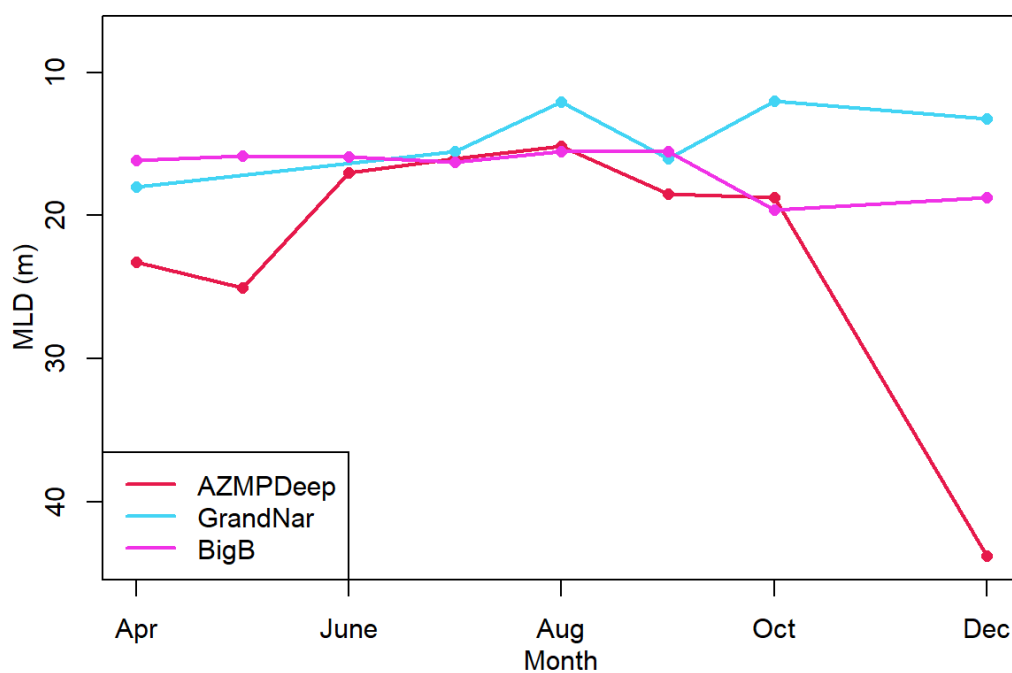


Figure D.5. Mean mixed layer depth (MLD) at AZMPDeep (red), GrandNar (blue), and BigB (pink) averaged across all years.

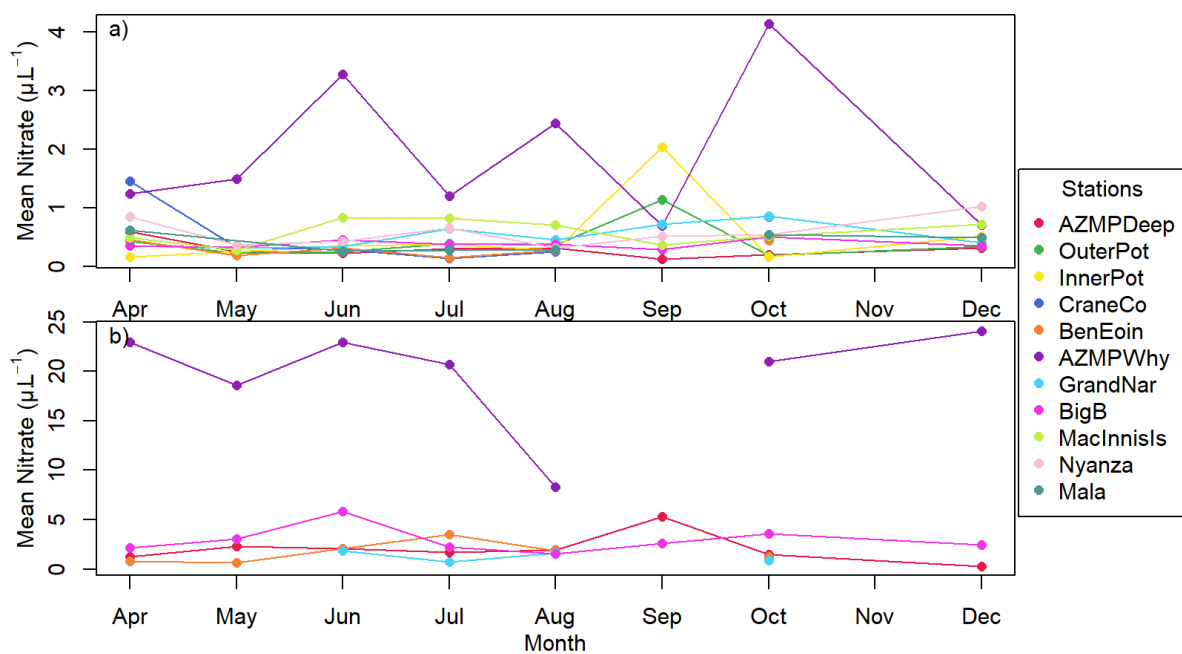


Figure D.6. Mean monthly nitrate (nitrate + nitrite + ammonium) concentration a) in the top 20 m and b) below 20 m by station averaged across all years.

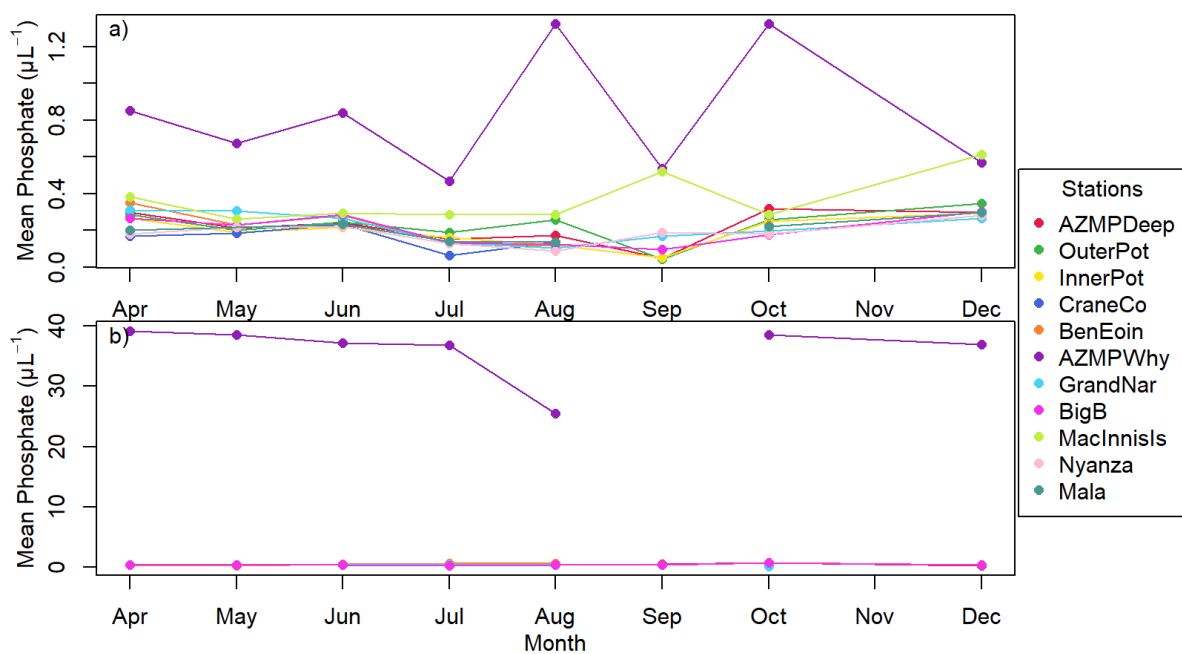


Figure D.7. Mean monthly phosphate concentration a) in the top 20 m and b) below 20 m by station averaged across all years.

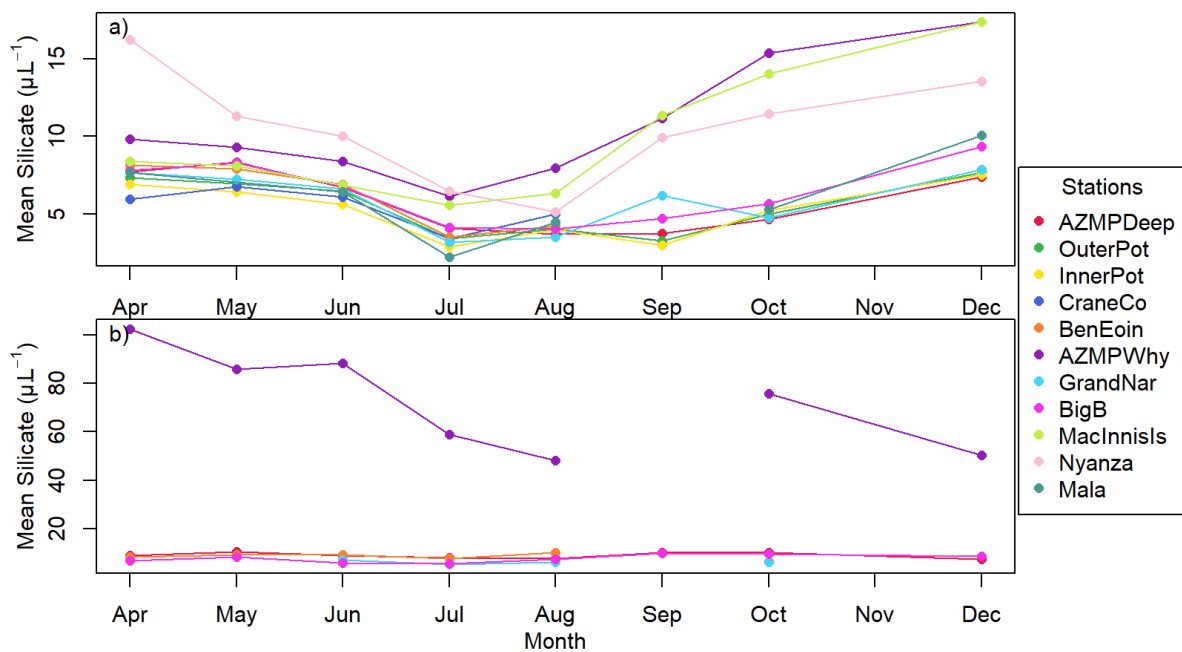


Figure D.8. Mean monthly silicate concentration a) in the top 20 m and b) below 20 m by station averaged across all years.

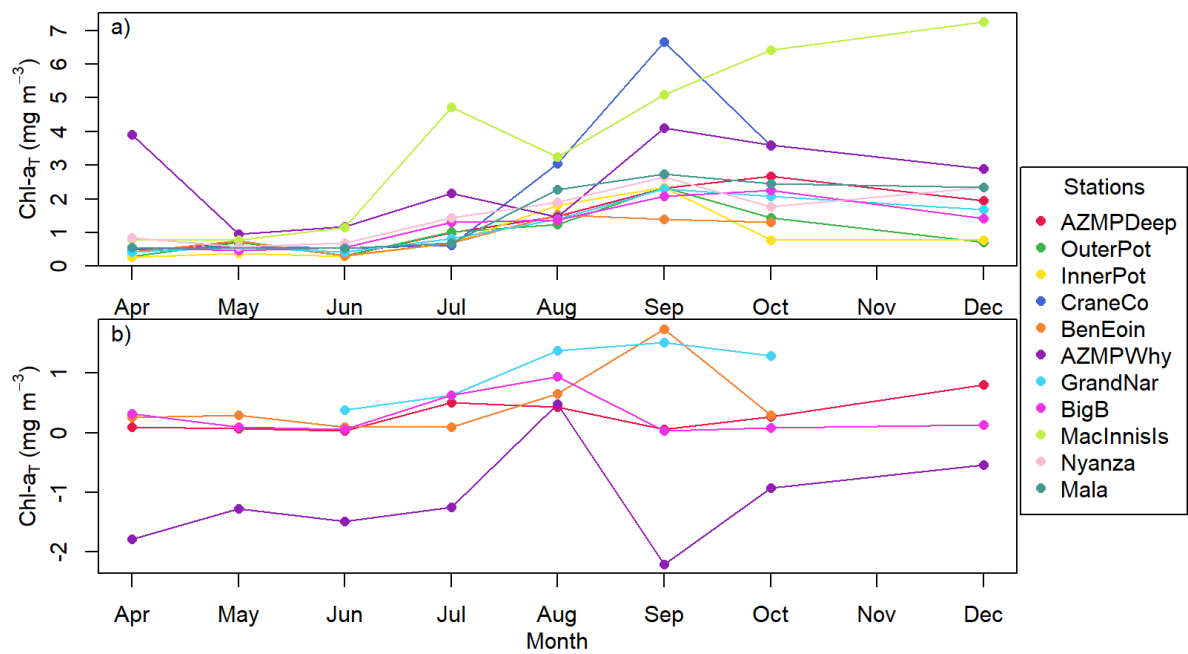


Figure D.9. Mean monthly turner chlorophyll-a concentration a) in the top 20 m and b) below 20m by station averaged across all years.

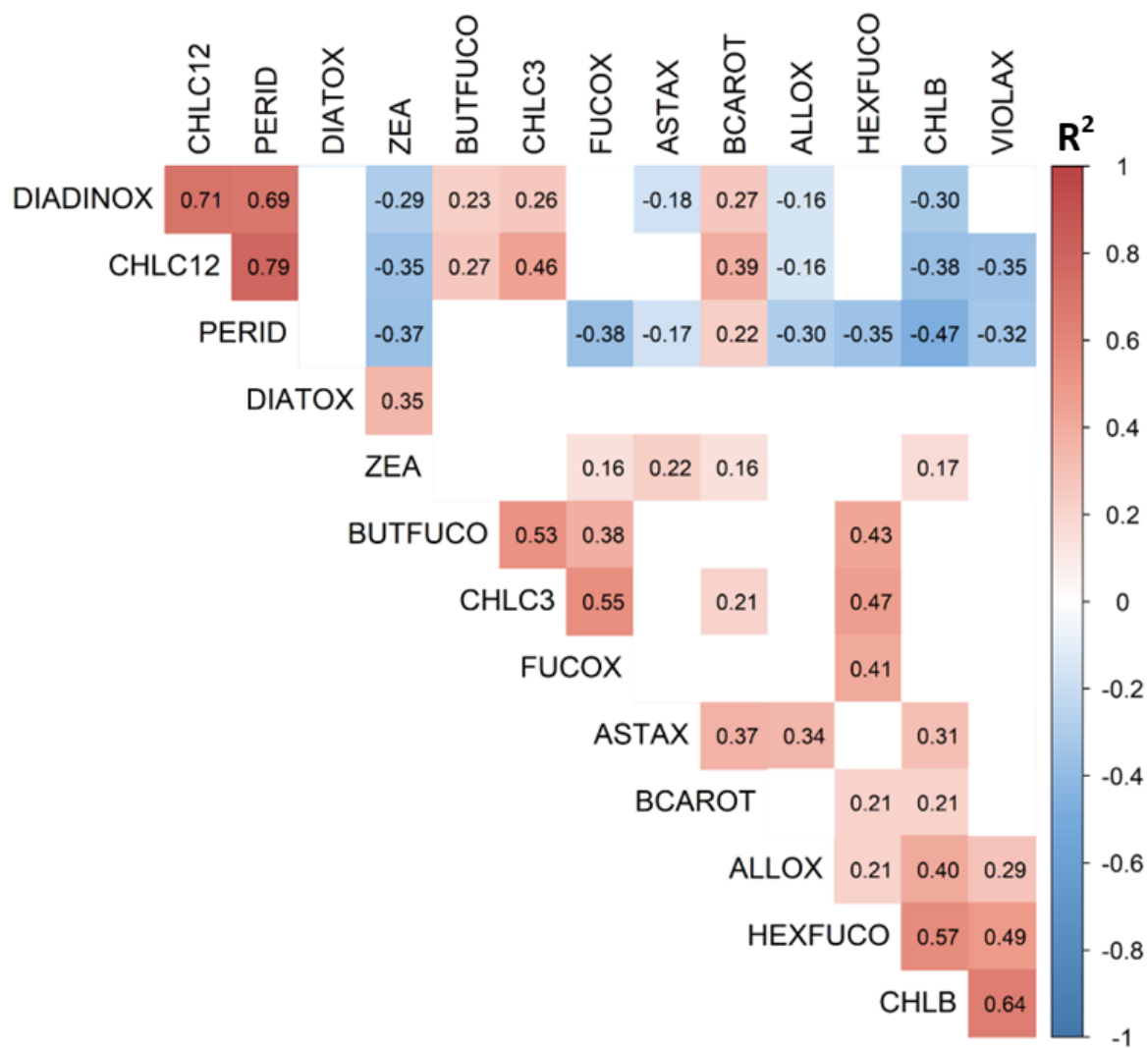


Figure D.10. Correlation matrix for phytoplankton pigments, white square indicates p-value > 0.01.

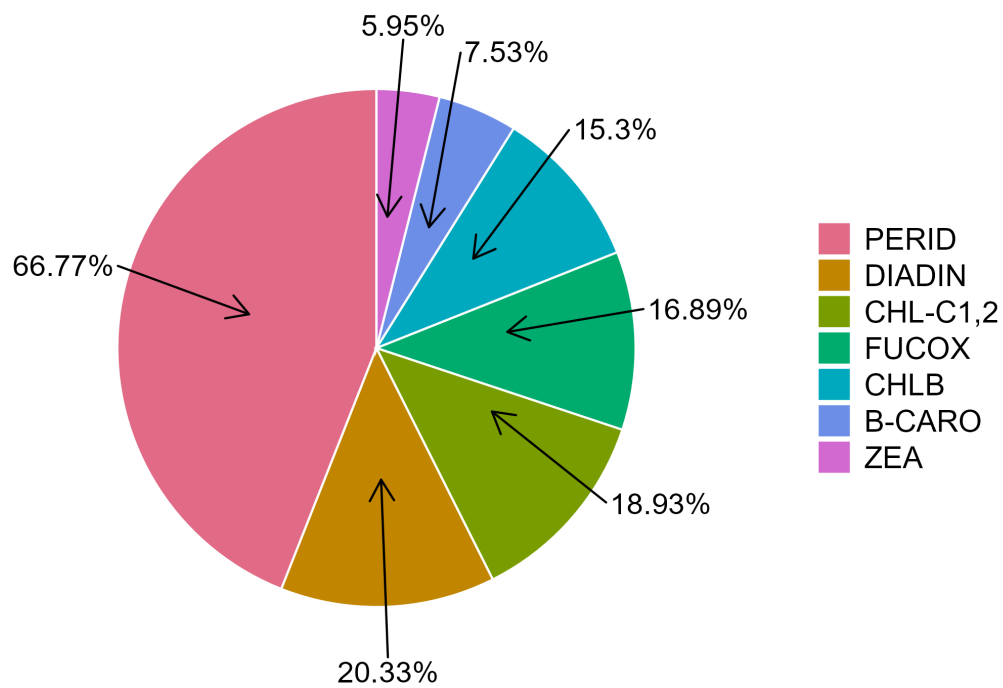


Figure D.11. Relative mean concentration for the most abundant seven pigments for all stations and all months.

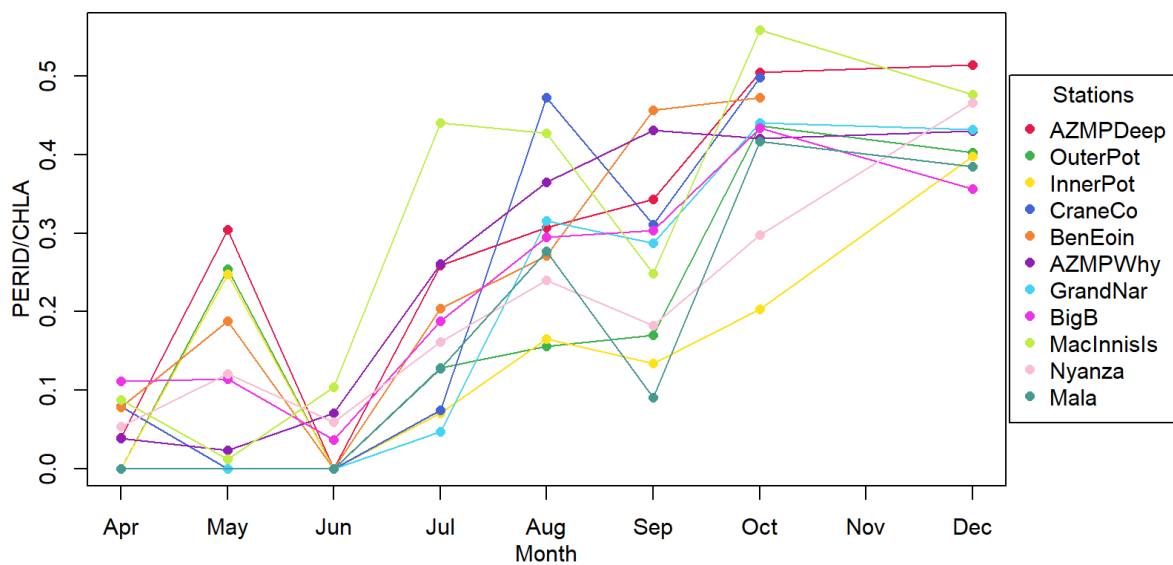


Figure D.12. Monthly mean Peridinin to chlorophyll-a ratio in the top 20 m per station averaged across all years.

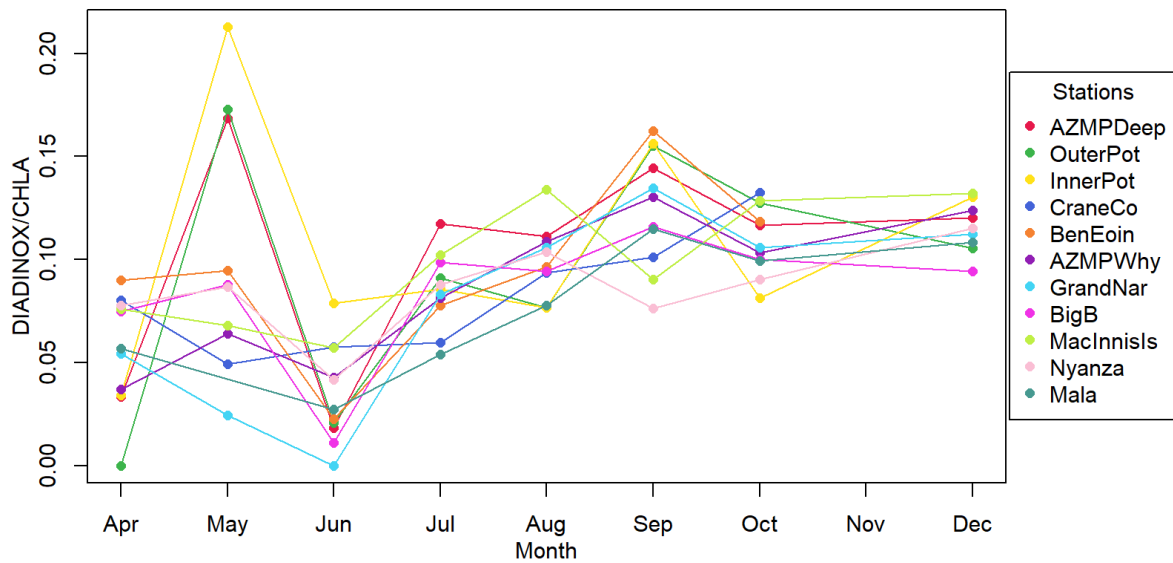


Figure D.13. Monthly mean Diadinoxanthin to chlorophyll-a ratio in the top 20 m per station averaged across all years.

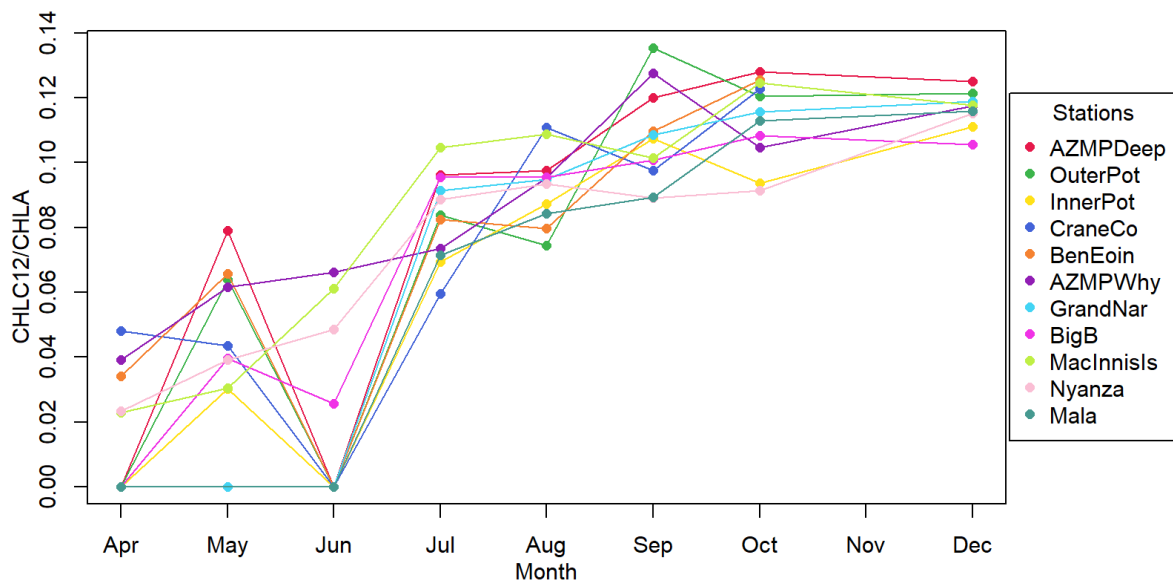


Figure D.14. Monthly mean chlorophyll c1,2 to chlorophyll-a ratio in the top 20 m per station averaged across all years.

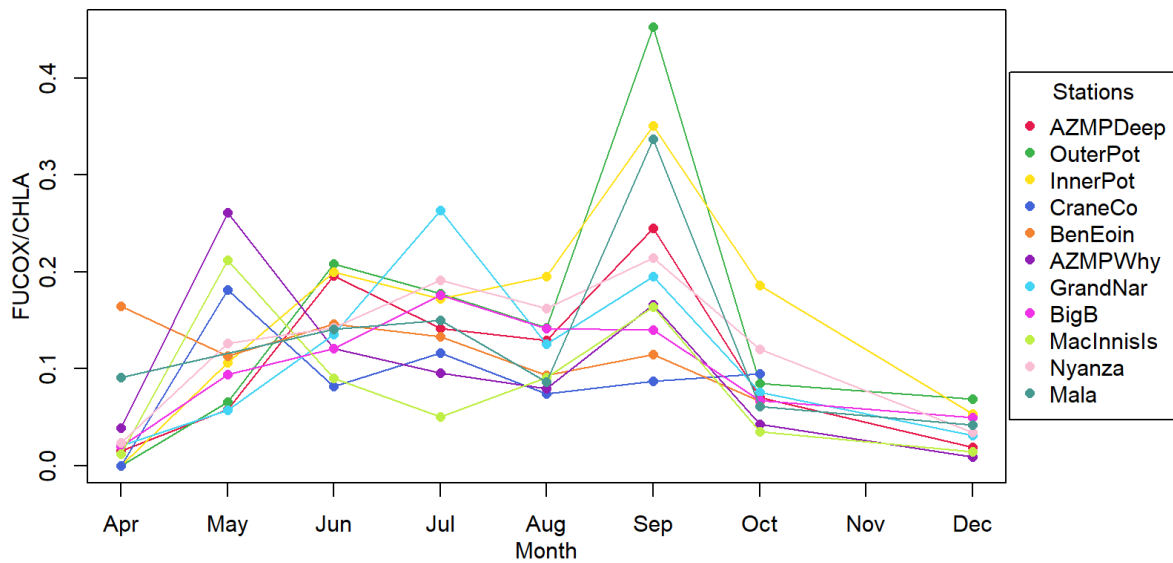


Figure D.15. Monthly mean Fucoxanthin to chlorophyll-a ratio in the top 20 m per station averaged across all years.

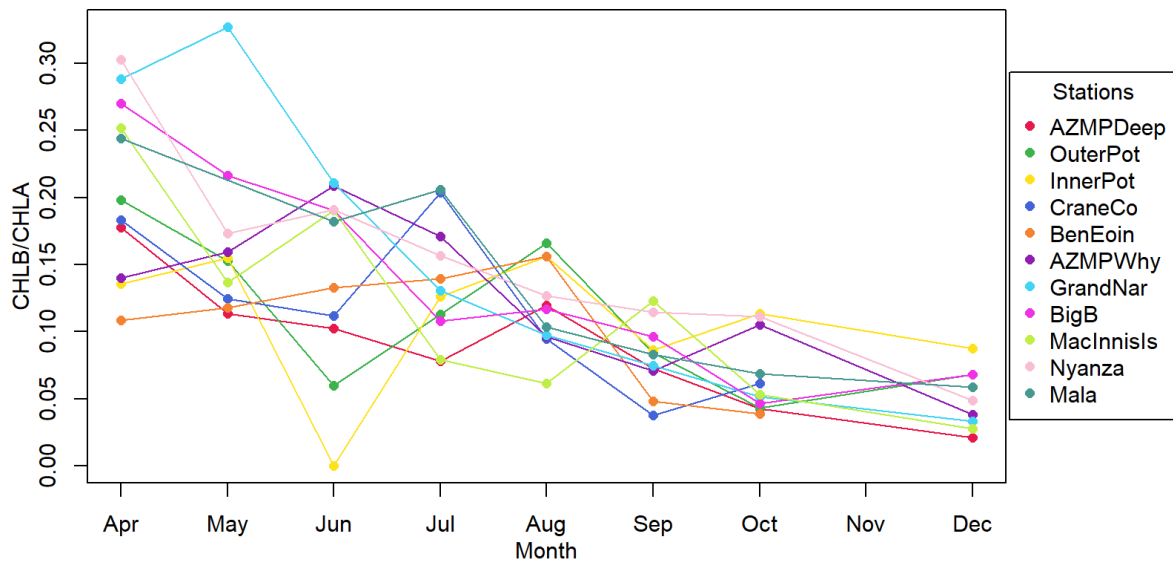


Figure D.16. Monthly mean chlorophyll-b to chlorophyll-a ratio in the top 20 m per station averaged across all years.

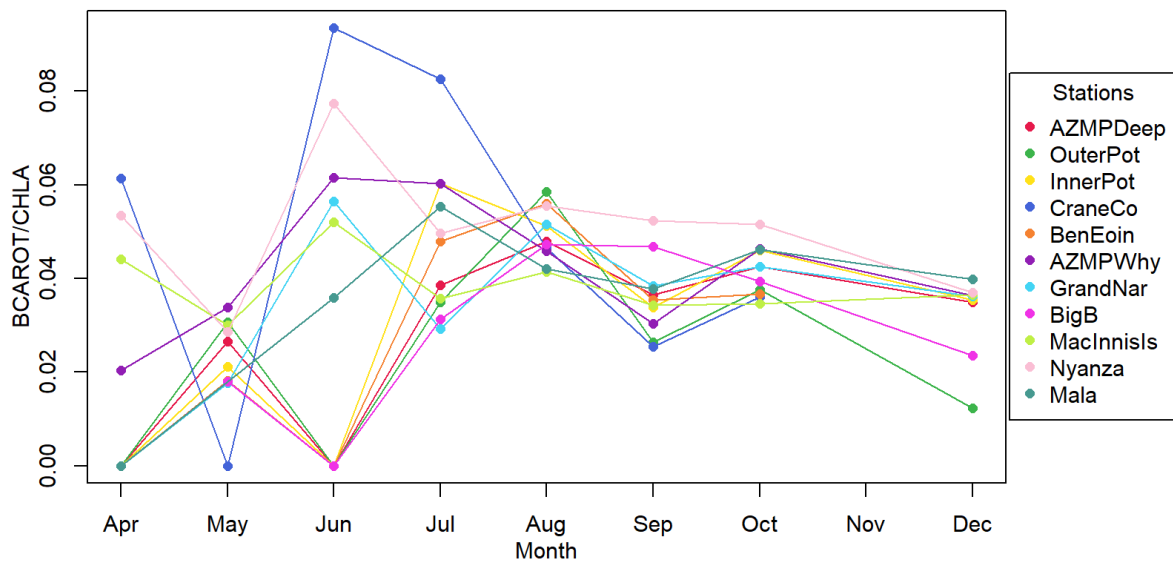


Figure D.17. Monthly mean β -carotene to chlorophyll-a ratio in the top 20 m per station averaged across all years.

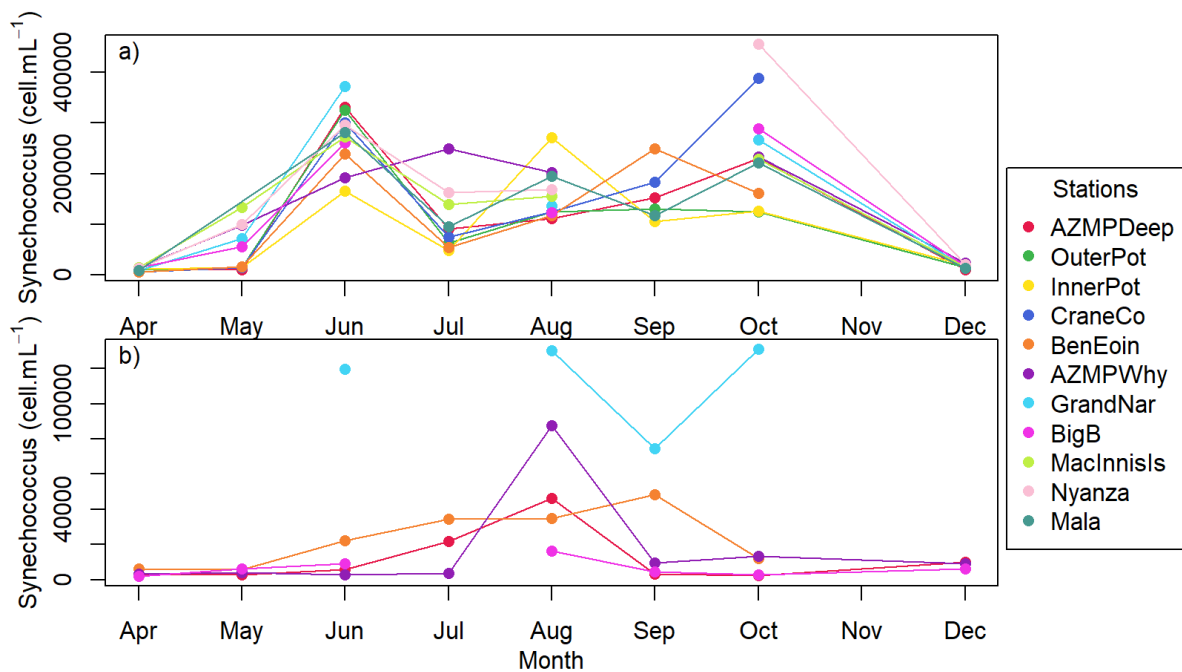


Figure D.18. Monthly mean synechococcus spp. abundance a) in the top 20 m and b) below 20 m per station averaged across all years.

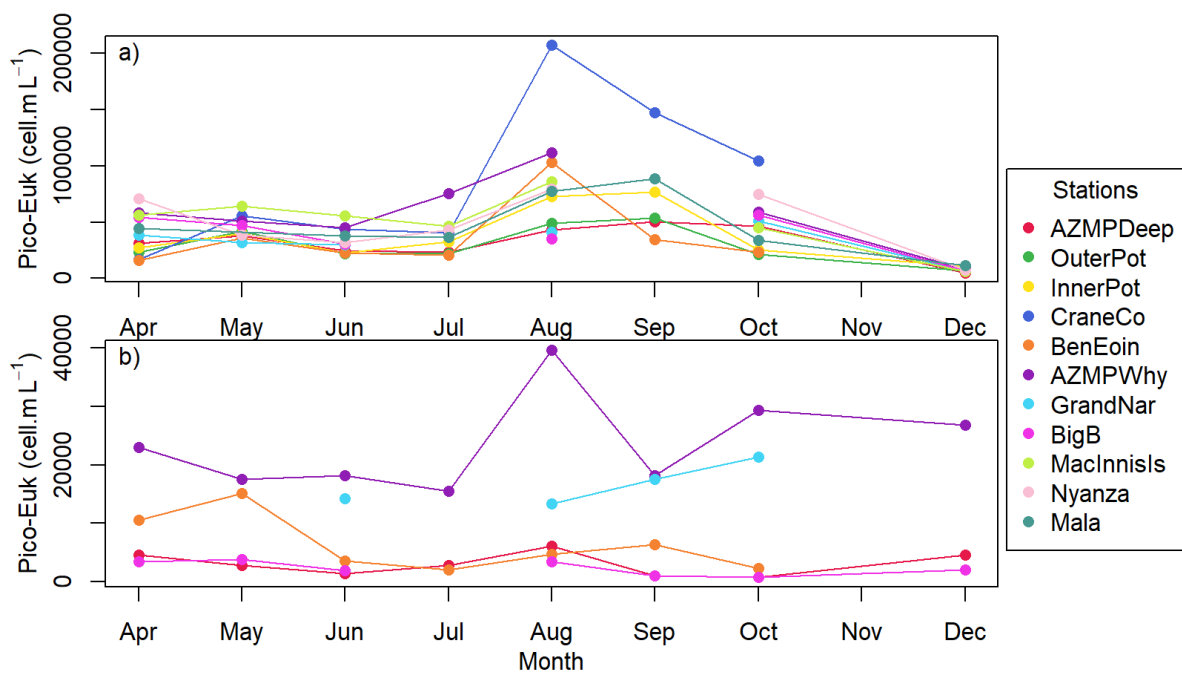


Figure D.19. Monthly mean pico-eukaryote abundance a) in the top 20 m and b) below 20 m per station averaged across all years.

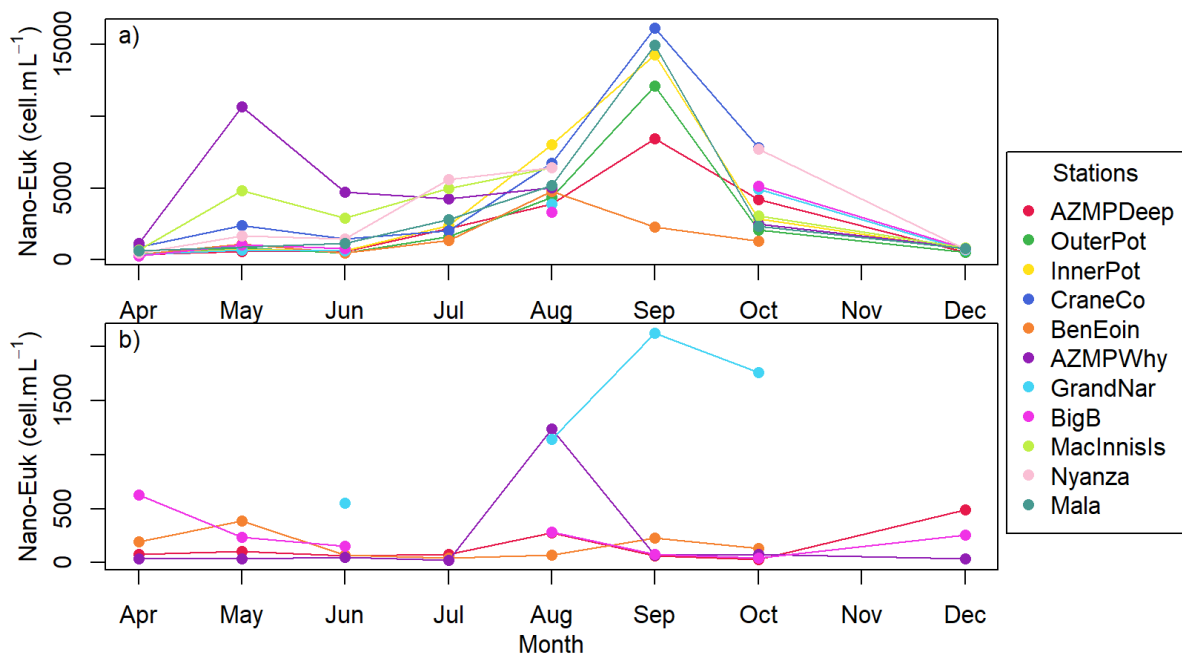


Figure D.20. Monthly mean nano-eukaryote abundance a) in the top 20 m and b) below 20 m per station averaged across all years.

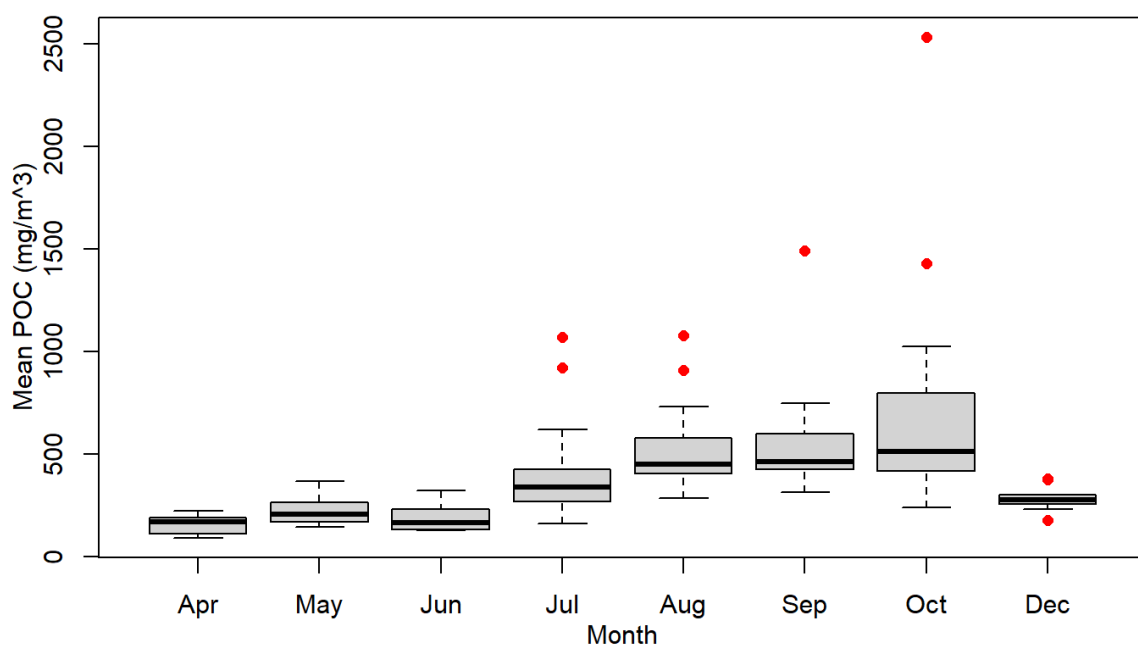


Figure D.21. Boxplot for the mean particulate organic carbon (POC) at the surface (1 m) for all stations averaged across all years. Red points indicate outliers.

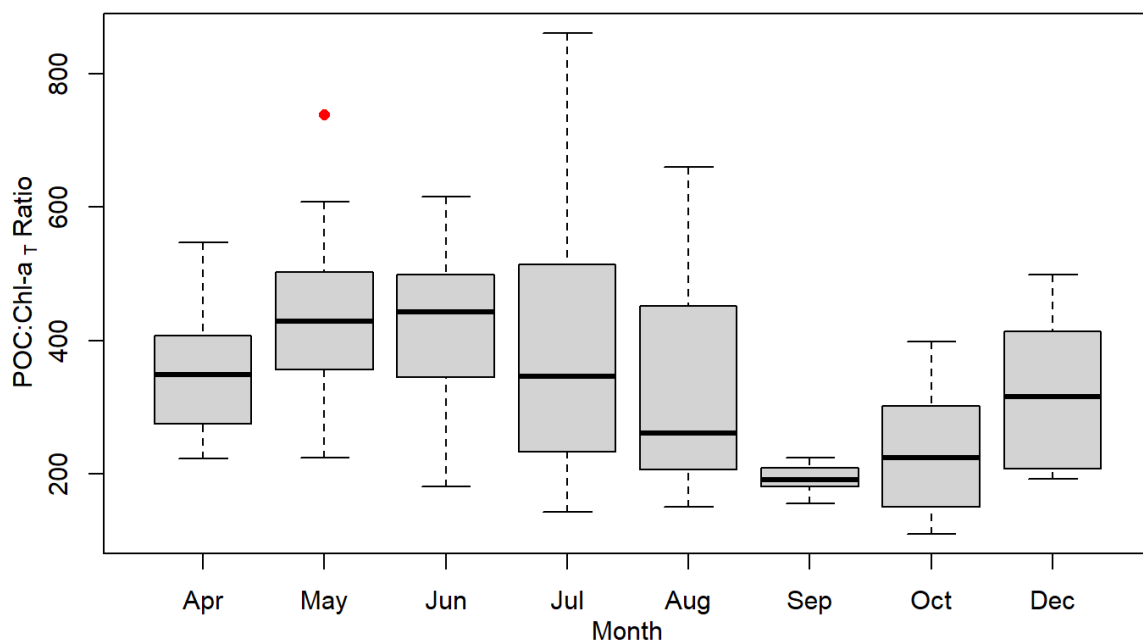


Figure D.22. Boxplot of the mean particulate organic carbon (POC) to mean chlorophyll-a ratio at the surface (1 m) for all stations averaged across all years. Red points indicate outliers.

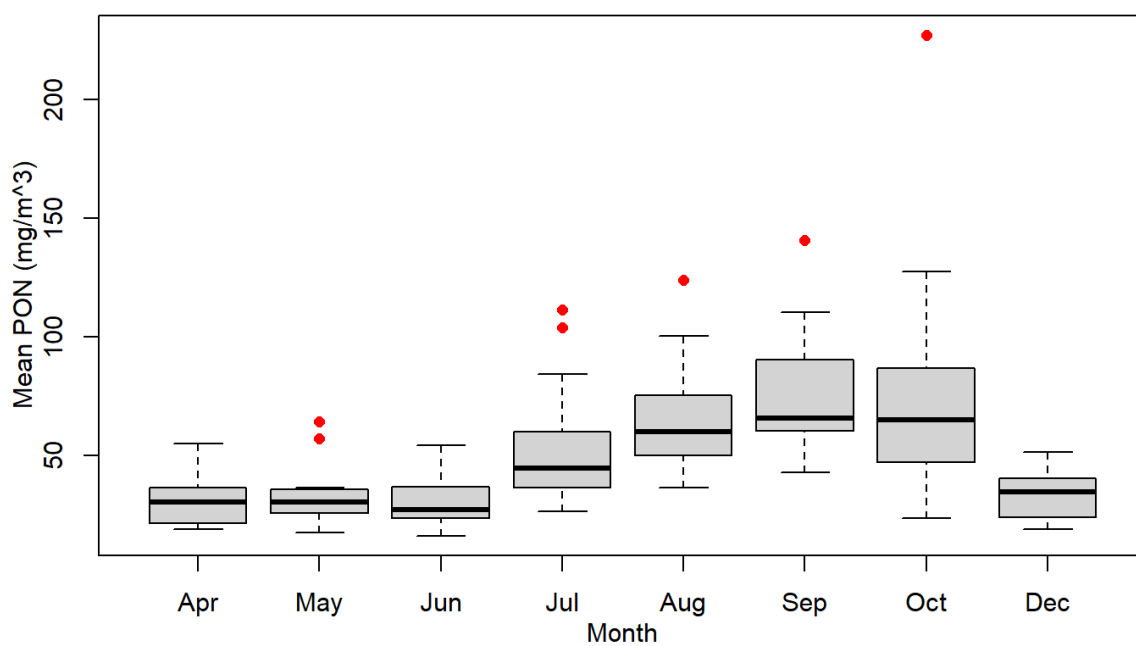


Figure D.23. Boxplot for the mean particulate organic nitrogen (PON) at the surface (1 m) for all stations averaged across all years. Red points indicate outliers.

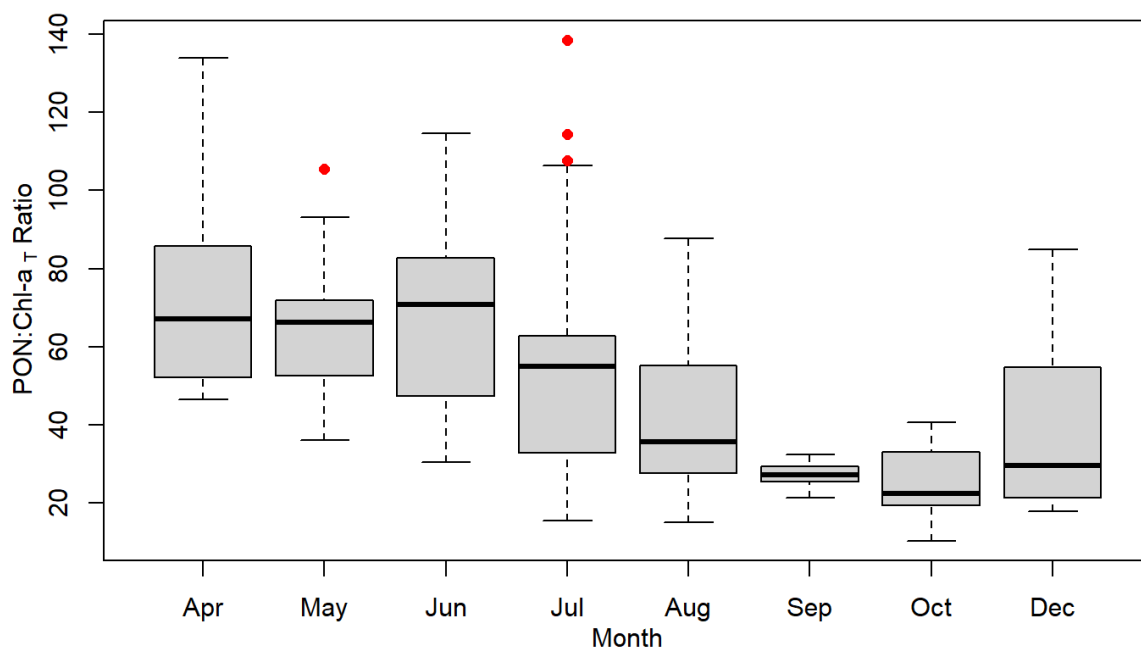


Figure D.24. Boxplot of the mean particulate organic nitrogen (PON) to mean chlorophyll-a ratio at the surface (1 m) for all stations averaged across all years. Red points indicate outliers.

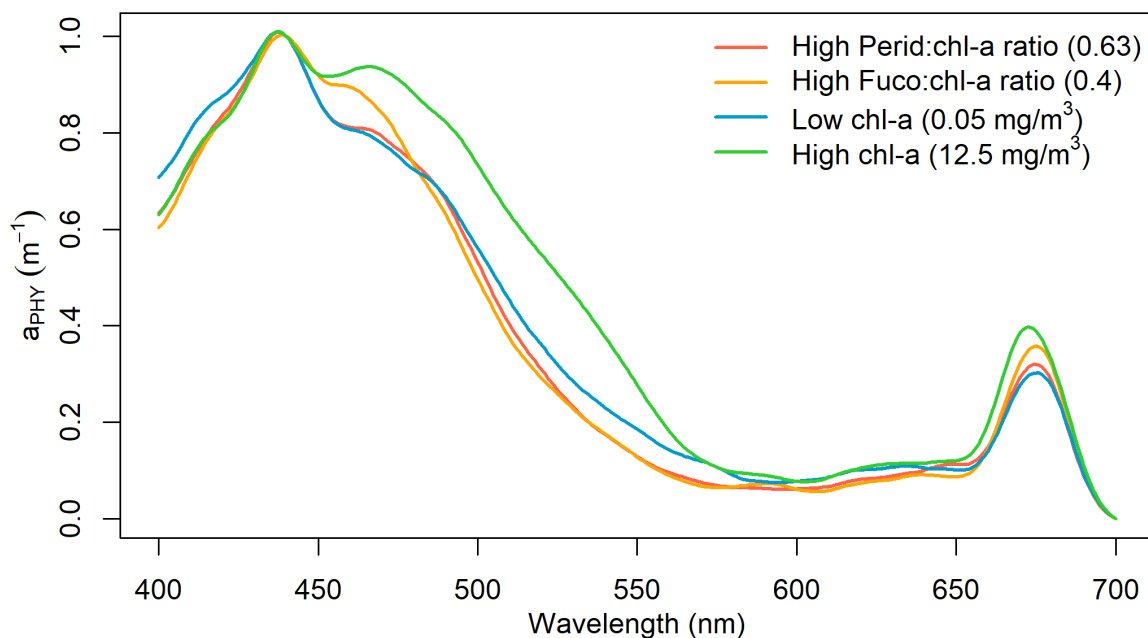


Figure D.25. Examples of phytoplankton absorption coefficients for different biomass and phytoplankton assemblages at four stations. High Perid:chl-a ratio corresponds to CranceCo, high Fuco:chl-a ratio corresponds to OuterPot, low chl-a concentration corresponds Mala, and high chl-a concentration corresponds MacInnisIs.

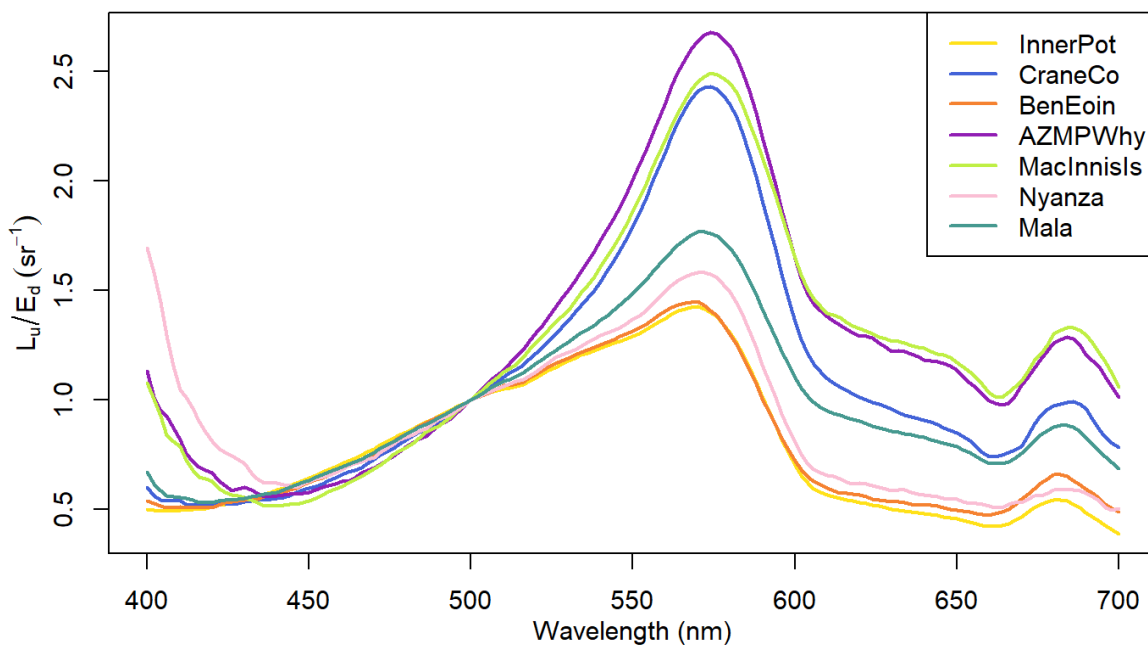


Figure D.26. Examples of reflectance collected at 1.5 m in October 2022. Note that these measurements need further processing to be converted into remote sensing reflectance.

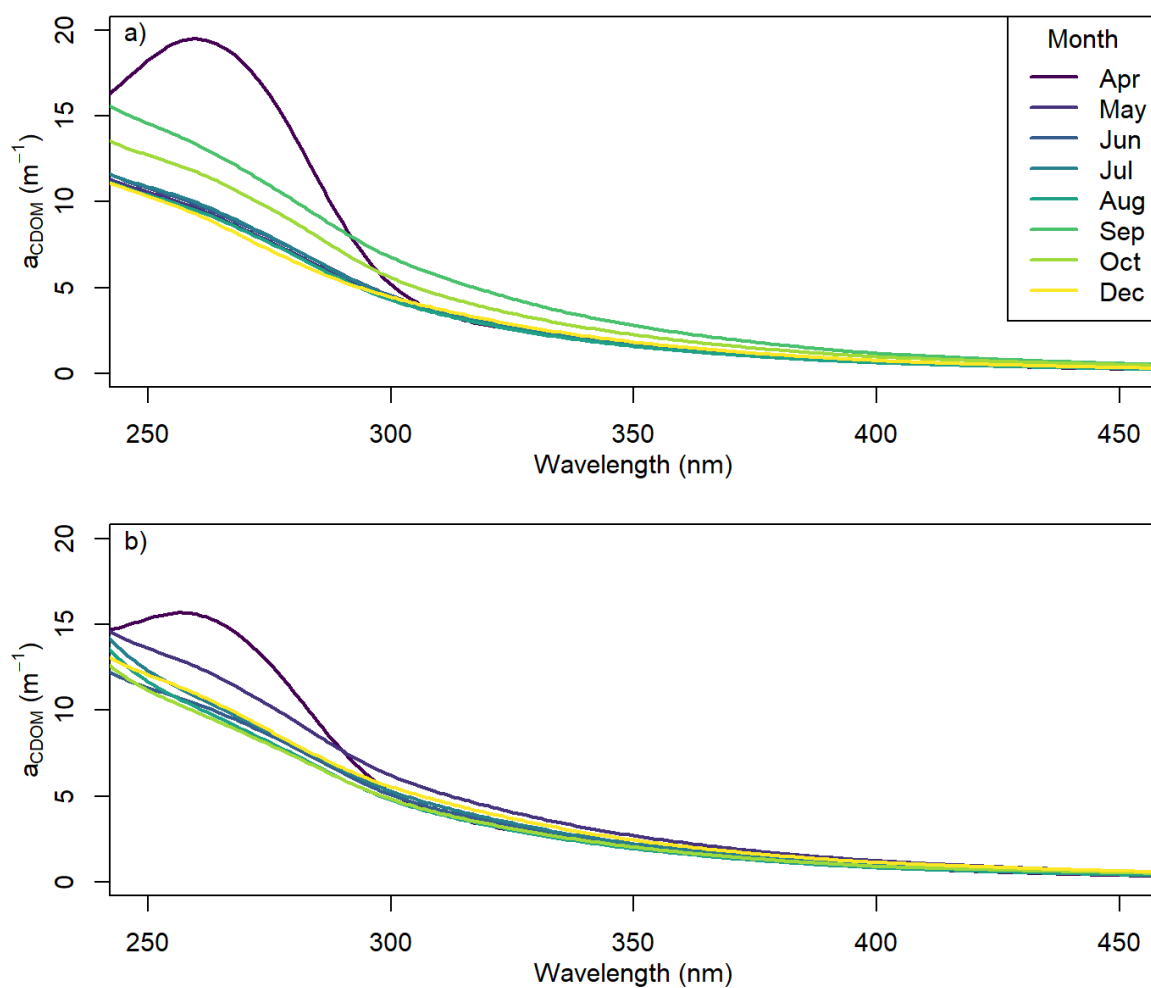


Figure D.27. Monthly mean coloured dissolved organic matter (CDOM) absorption a) in the top 20 m and b) below 20 m by month of all stations averaged across all years.

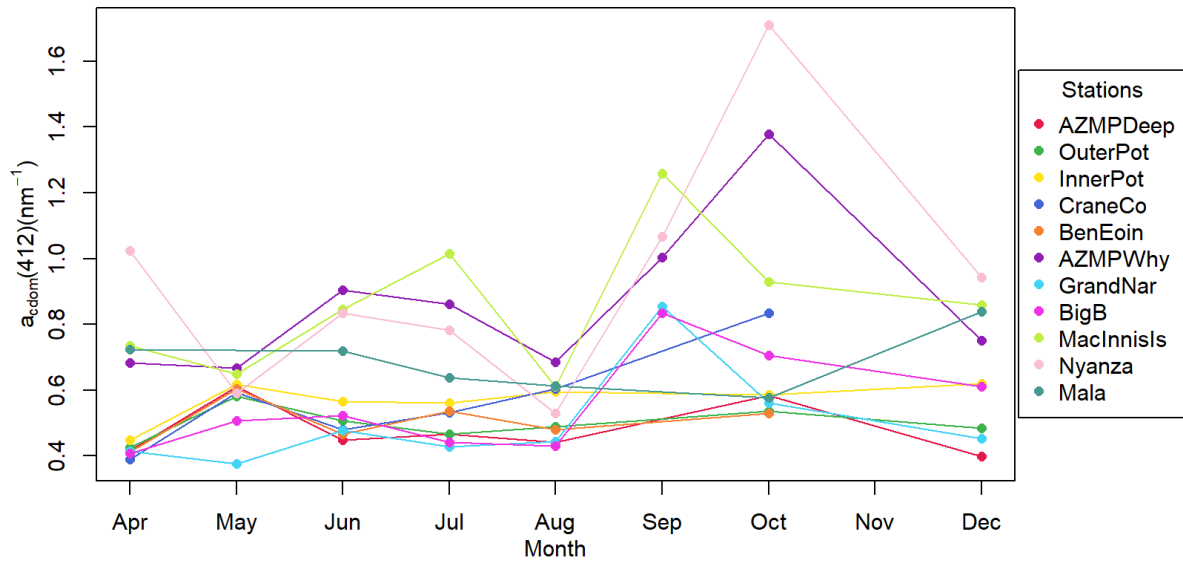


Figure D.28. Monthly mean of CDOM absorption at 412 nm per station averaged across all years.

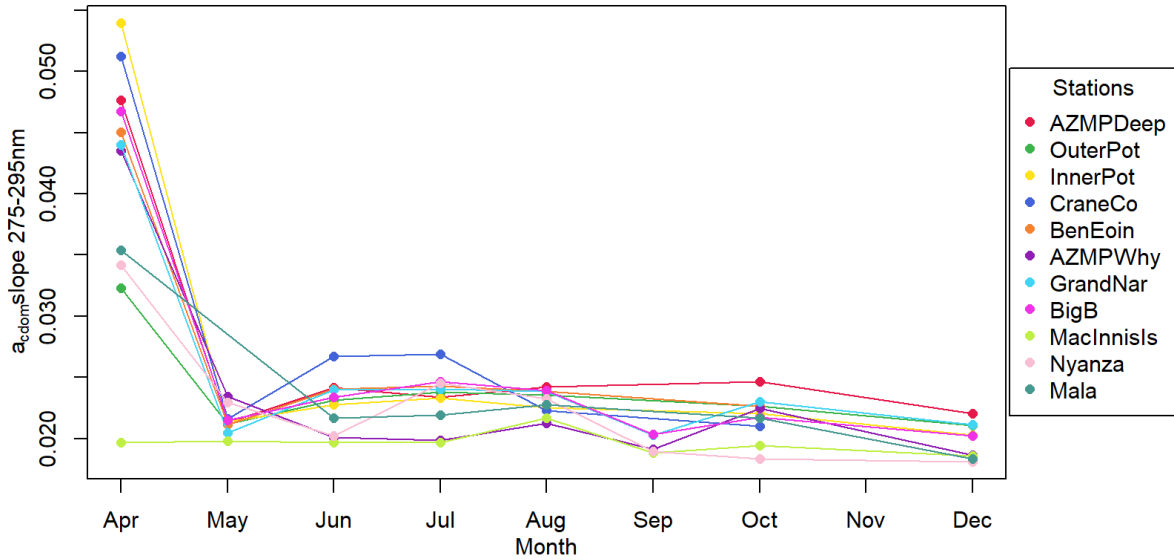


Figure D.29. Monthly mean slope of the exponential decrease of CDOM absorption coefficient between 275 and 295 nm per station averaged across all years.

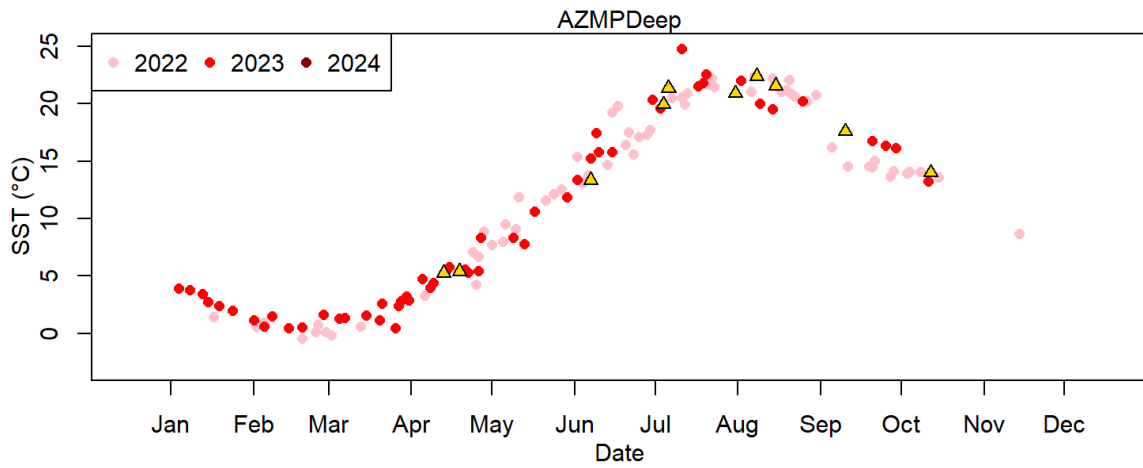


Figure D.30. Time-series of the mean SST (°C) from the 250km MODIS satellites as well as surface in situ measurements (yellow triangles) collected from the CTD for AZMPDeep. Note there is no MODIS data for 2024 due to processing issues.

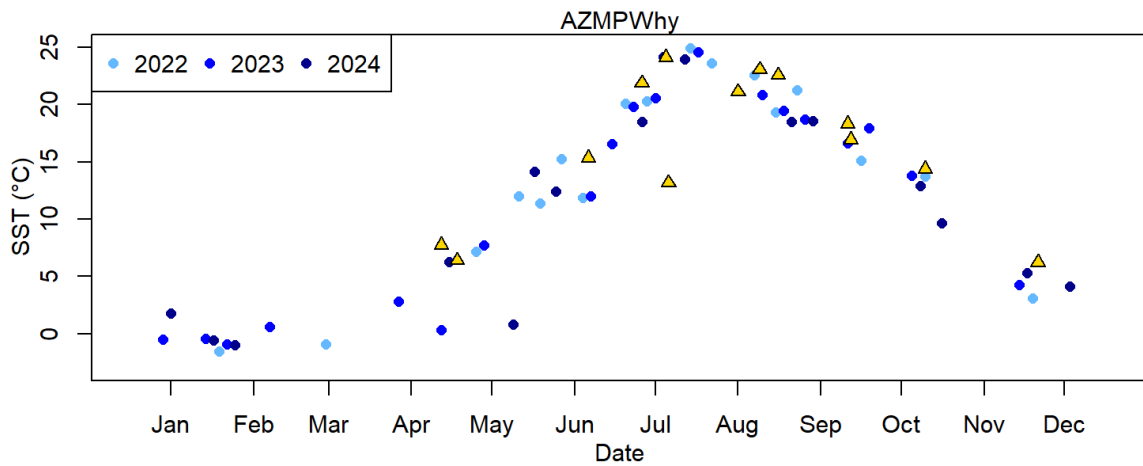


Figure D.31. Time-series of the mean SST (°C) from 60m Landsat satellites as well as surface in situ measurements (yellow triangles) collected from the CTD for AZMPWhy.

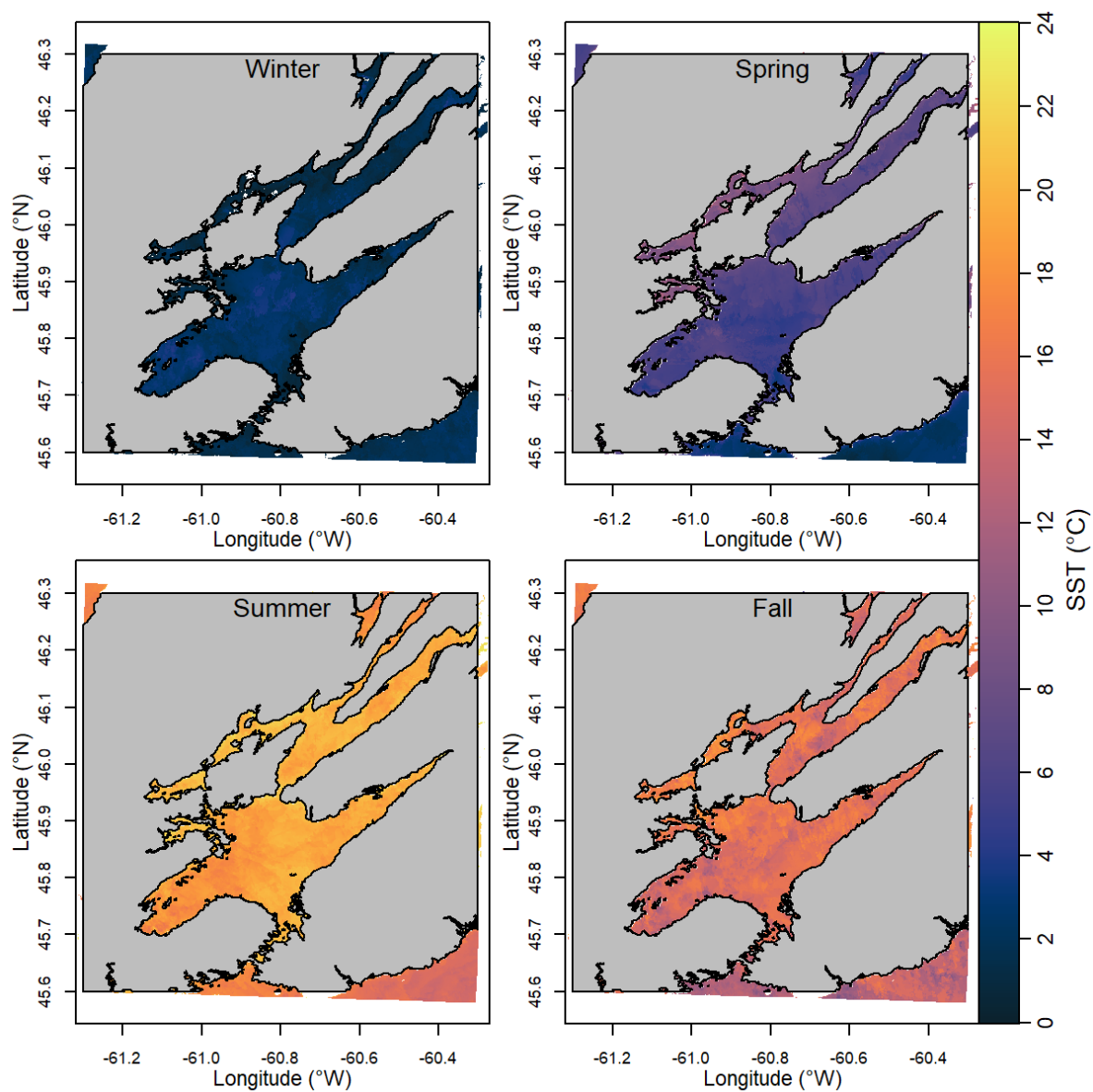


Figure D.32. Seasonal mean sea-surface temperature of Pitu'paq from 2022 to 2024 using daily Landsat images, 60 m resolution.