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Biogeochemical oceanographic conditions in the Northwest Atlantic (NAFO subareas 2-3-4) during 2021

by

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Abstract

This report review the spatial and inter-annual variation in biogeochemical indices derived from satellite observations (spring phytoplankton bloom initiation, duration and magnitude) and from direct measurement of oceanographic variables (nitrate and chlorophyll-*a* concentration, and zooplankton abundance and biomass) by the Atlantic Zone Monitoring Program (AZMP) across a network of cross-shelf sections and high-frequency monitoring sites spanning NAFO Subareas 2, 3 and 4. Spring bloom initiation, duration, and magnitude in 2021 were either near or below (i.e., earlier bloom initiation) long-term average in all subregions (EPUs or GSL) except for the late bloom timing on the Georges Bank, the longer bloom duration on the Newfoundland Shelf, and for the higher spring production on the Scotian Shelf. Mean integrated nitrate and chlorophyll inventories were also near normal in 2021 and the missing data from the cancelled spring surveys certainly contributed to the negative anomalies observed on the Newfoundland Shelf and the Scotian Shelf. The abundance of copepods, and more specifically that of the large, energy-rich, *Calanus finmarchicus,* was generally higher in the NL Region compared to the Scotian Shelf and the Gulf of St. Lawrence which was also reflected in the total zooplankton biomass index. Mean abundance of non-copepod zooplankton was above normal for a 7th consecutive year in 2021 with positive anomalies in all subregion except for the small negative anomaly on the Scotian Shelf.

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1. Introduction

Here, we review the biogeochemical oceanographic conditions in Northwest Atlantic (NWA) shelf waters within NAFO Subareas 2, 3 and 4. We present results collected in 2021, and reference earlier periods where data are available. Satellite ocean colour observation and seasonal sampling of oceanographic sections and high-frequency monitoring sites by the Atlantic Zone Monitoring Program (AZMP) provided reasonable spatial and temporal series coverage. Annual collection of standard variables (nutrients, chlorophyll-*a* , and zooplankton and) since 1999 (AZMP) or 2003 (MODIS satellite sensor), allows to compare spatial and temporal patterns of variation among ecologically relevant biogeochemical indices in the NW Atlantic. We used NAFO Ecological Production Units (EPUs) and the Gulf of St. Lawrence as grouping units to summarise biogeochemical indices at a scale deemed to be suited for integrated ecosystem management plans in the NW Atlantic (Koen-Alonso et al. 2019; see Fig. 1 for EPUs location). Additional details on physical, chemical and biological oceanographic conditions in the NW Atlantic in 2020 and earlier years can be found in Maillet et al. (2022), Blais et al. (2021), Galbraith et al. (2021), Hebert et al. (2021), Cyr et al. (2021), Yashayaev et al. (2021), Casault et al. (2020).

2. Methods

Surface chlorophyll *a* concentration across the NWA was obtained from ocean colour observations from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellite sensor (http://modis.gsfc.nasa.gov/). Daily composite images of surface chlorophyll concentration were used to characterise the phenology of the spring phytoplankton bloom over the period covered by MODIS, i.e., 2003-present. A shifted Gaussian function of time was used to estimate spring bloom initiation, duration, and magnitude (total production) within subareas of the NWA continental shelf (see Fig. 2A for satellite boxes location) following a method adapted from Zhai et al. (2011).

Collection of standard AZMP variables (integrated nitrate [50-150 m] and chlorophyll *a* [0-100 m] inventories, total abundance of copepods, non-copepods, *Calanus finmarchicus* and *Pseudocalanus* spp. abundance, and total zooplankton biomass) followed protocols outlined in Mitchell *et al*. (2002). Observations for 2021 and earlier years presented in this document are based on seasonal surveys conducted in spring, summer and fall (typically

March through December) along standard AZMP oceanographic sections and at high-frequency monitoring sites sampled at a weekly to monthly intervals during the ice-free period of the year (see Fig 2B for the location of oceanographic sections and monitoring sites). Anomalies were used to summarize spatial and temporal variability in the biogeochemical environment and at the lower trophic levels. Annual standardized anomalies were calculated for each selected variable by subtracting the mean of the reference period (RP) from the annual mean observation and by dividing the result by the standard deviation (SD) for the reference period ([observation – mean RP]/SD RP). Anomalies for the spring bloom indices (bloom initiation and magnitude) were calculated on log-transformed data. Annual standardized anomalies for nitrate, chlorophyll, copepod, non-copepod, *Calanus finmarchicus*, and *Pseudocalanus* spp, and zooplankton biomass were calculated using the least square means of linear models that included the fixed factors Year, Season and Station (standard oceanographic sections) or Year and Season (High-frequency monitoring sites) fitted to log-transformed data (ln (x+1)). The results of this standardization yielded a series of annual anomalies that illustrate departures from the long-term average conditions, or climatology, across the range of variables. The difference between a given year and the climatological mean represents the magnitude of that departure from the reference period. The reference periods used are 2003-2020 for the satellite-derived spring bloom indices, and 1999-2020 for AZMP biogeochemical indices.

Anomaly values within ± 0.5 SD from the climatological mean are representative of near-normal conditions. Positive anomalies > 0.5 SD indicate conditions above (or later for bloom initiation) the climatological mean. Negative anomalies < 0.5 SD indicate conditions below (or earlier for bloom initiation) the climatological mean. Annual standardized anomalies of each oceanographic sections and high-frequency monitoring sites were averaged over NAFO EPUs (Labrador Shelf [LS], Newfoundland Shelf [NS], Flemish Cap [FC], Grand Bank [GB], Southern Newfoundland [SN], Scotian Shelf [SS], and Georges Bank [GB]) and the Gulf of St. Lawrence to provide an estimate of the overall oceanographic trends within each geographical grouping unit. The standard AZMP variables selected were: spring bloom initiation (day of year), and magnitude (mg · m^{-3} · d^{-1}); 50-150 m integrated nitrate (mmol · m^{-2}); 0-100 m integrated chlorophyll *a* (mg · m^{-2}); copepod, non-copepod, *Calanus finmarchicus*, and *Pseudocalanus* spp. abundance (ind. · m^{-2}); and total zooplankton biomass (g · dry weight · m^{-2}). To estimate broad-scale spatial trends across the NW Atlantic, a weighted mean anomaly index was calculated for each sampling year by summing the annual anomalies of each AZMP oceanographic sections and high-frequency monitoring sites and dividing the results by the number of sections and sites included in the calculation.

We produced a Pearson correlation matrix to quantify the strength of the relationships between the various biogeochemical indices presented above and the physical environment using the ocean climate index developed by Cyr and Galbraith (2021) for the Newfoundland and Labrador region. We used annual anomalies of the composite climate index and of a subset of the its components, namely the winter NAO index, air temperature, sea ice extent, sea surface temperature, and bottom temperature. Biogeochemical anomalies from the Scotian Shelf and the Gulf of St. Lawrence were not included in the correlation calculations because these regions are not covered by the climate index.

Limited availability of scientific research vessels in 2021 lead to the cancellation (spring and fall surveys for the Newfoundland and Labrador region, and spring survey for the Maritimes region) or the reduction (spring survey for Gulf of St. Lawrence region). As a consequence, the Southeast Grand Bank and the Southeast and Southwest St. Pierre Bank oceanographic sections in the NL region were not sampled in 2021. In addition, logistical considerations delayed the analysis of zooplankton samples from the Scotian Shelf region and abundance and biomass data from this region were only available for the Halifax 2 monitoring site at the time of writing of this report. Therefore, the 2021 biogeochemical indices (nitrate, chlorophyll, and zooplankton abundance and biomass) derived from *in situ* observations during AZMP seasonal oceanographic campaigns, especially those for the NL and SS EPUs where whole surveys were missing, should be interpreted with caution.

3. Annual variability in nutrient, phytoplankton, and zooplankton inventories in NAFO Subareas 2-4

3.1. Phytoplankton spring bloom

The initiation of the spring phytoplankton bloom along the eastern Canadian Shelf occurs earlier in the south compared to regions to the north. On average, the spring bloom begins between late March and early April on the Georges Bank, Scotian Shelf, Gulf of St. Lawrence and Southern Newfoundland, and ~1 week earlier on the Grand Bank and the Flemish Cap (Fig. 3A). Bloom initiation typically occurs in mid- to late April on the Newfoundland Shelf, and up to one month later on the Labrador Shelf (Fig. 3A). Extensive sea ice cover on the Labrador Shelf in the spring delays the initiation of the bloom in that region. The onset timing of the spring bloom in NW Atlantic shelf waters varies spatially and interannually with no overall clear signal. There was a period of mostly early to near-normal bloom onset across the zone from 2004 to 2006, and another period of mostly later-than-normal blooms on the Newfoundland Shelf, Flemish Cap, Grand Bank and Southern Newfoundland from 2014 to 2017 (Figure 4A). For the remaining years, bloom initiation timing was variable with no broad-scale spatial or temporal signal besides the notably early blooms observed across most of the zone in 2010 (Figure 4A). In 2021, spring bloom initiation was earlier than normal on the Labrador Shelf, Newfoundland Shelf, Flemish Cap, and Scotian Shelf, near-normal on the Grand Bank, Southern Newfoundland and in the Gulf of St. Lawrence, and at a time series record late on the Georges Bank (Figure 4A). Overall, the spring bloom onset has been happening slightly earlier over the past few years compared to conditions observed during the mid-2010s (Figure 4A).

The duration of the spring bloom generally increases with latitude from ~30-35 days on the Georges Bank and the Scotian Shelf, to ~40-60 days on Grand Bank, the Newfoundland Shelf and the Labrador shelves (Fig. 3B). Bloom duration is more variable on the Georges Bank (~20-45 d) and the Flemish Cap where blooms tend to be longer (~60-95 d) than in other regions (Fig. 3B). Bloom duration was variable with no clear long-term spatial or temporal trends throughout the time series (Fig. 4B). In 2021, mean bloom duration was shorter than normal on the Labrador Shelf, Grand Bank and Georges Bank, near normal on the Flemish Cap and on the Southern Newfoundland, Gulf of St. Lawrence and Scotian Shelf for a second consecutive year, and longer than normal on the Newfoundland Shelf (Figure 4B).

The magnitude (total production) of the spring bloom varies considerably among regions, being minimum in the north on the Labrador Shelf, intermediate in the south from Georges Bank to Southern Newfoundland, and maximum at mid-latitudes on the Grand Bank, the Flemish Cap and Newfoundland Shelf (Fig. 3C). Spring bloom production was quite variable during the first half of the time series, but remained mostly near or below normal across the zone from 2012 to 2017 before decreasing to mainly near of below-normal levels afterwards (Fig. 4C). In 2021, mean bloom production was below normal on the Grand Bank, Gulf of St. Lawrence and Georges Bank, near normal on the Labrador Shelf, Newfoundland Shelf, Flemish Cap and Southern Newfoundland, and above normal on the Scotian Shelf (Fig. 4C). Overall, this represents a decrease in the spring primary production compared to the previous 3-4 years (Figure 4C).

3.2. Nitrate and chlorophyll-*a*

Mean annual anomalies of integrated (50-150 m) nitrate inventories decreased from near-to-above normal during the 2000s to near-to-below normal during the first half of the 2010s (Fig. 5A). Nitrate anomalies were typically lower for the Newfoundland and Labrador region (LS, NS, FC, GB and SN) compared to the Scotian Shelf and the Gulf of St. Lawrence during that 2010-2014 low nitrate period (Fig. 5A). Mean inventories have remained near normal since 2015 except for the low levels observes across the zone in 2018 (Fig. 5A). In 2021, small positive nitrate anomalies were recorded in all EPUs for an overall near-normal level across the zone (Fig. 5). Over the past two years, nitrate inventories decreased from near to below normal at Station 27 (3L) and from above to below normal on the eastern GSL (4RS) and at Rimouski Station (4T) (Fig. 6A). Nitrate inventories increased from near to above normal on the Bonavista (3K) and the shelf part (3L) of the Flemish Cap sections as well as on the Central Gulf of St. Lawrence (4RST), and on the central and eastern Scotian Shelf (Halifax 2 Station and Halifax and Louisbourg sections), and from below to near normal on the Brown Bank and at Prince 5 monitoring site (4X) during the same period (Fig. 6A). Overall, nitrate inventories in 2021 were mainly near or above normal across the zone with a few below normal records (Station 27, Eastern GSL, Rimouski) (Fig. 6A).

Integrated (0-100 m) chlorophyll-*a* inventories show a similar overall temporal trend to that of nitrate with periods of higher nitrate levels corresponding to higher chlorophyll inventories and vice versa (Fig. 5A, B). Concordance between broad-scale nitrate and chlorophyll trends is not surprising given that nitrate is the main limiting factor of oceanic primary production (Bristow et al. 2017). Mean anomalies for the zone indicated mainly near-normal chlorophyll levels during the 2000s, and near or below normal levels from 2011 through 2016 (Fig. 5B). Chlorophyll inventories increased since 2017 with positive anomalies in most EPUs and above-normal record for the zone in 2019 (Fig. 5B). In 2021, mean chlorophyll-*a* inventories were near normal but the negative anomalies on the NL Shelf contrasted with conditions observed during previous years (Fig. 5B). Although the missing data from the cancelled 2021 spring surveys on the Newfoundland Shelf may partly explain the lower chlorophyll-*a* values in that region, this is not the case for the Labrador Shelf where index calculation is based on summer data only. Over the past two years, chlorophyll inventories decreased from above to near normal on the Seal Island (2J) and 3M part of the Flemish Cap sections as well as in the Southern Gulf of St. Lawrence (4T), and from near to below normal on the Makkovik (2H) and Bonavista (3K) sections and at the Prince 5 (4X) monitoring site (Fig. 6B). Chlorophyll inventories increased from below to near normal at the Halifax 2 monitoring site (4W) and from near to above normal in the Central Gulf of St. Lawrence (4RST) and at the Rimouski monitoring site (4T) (Fig. 6B). Overall chlorophyll-*a* inventories were mainly near normal in 2021 with some low records on the NL Shelf (2H, 3K) and in the Bay of Fundy (4X), and higher records for the Gulf of St. Lawrence (4RST) (Fig. 6B).

3.3 Zooplankton abundance

Copepods numerically dominate zooplankton assemblages in Canadian shelf waters (Maillet et al. 2022, Casault et al., 2020, Blais et al. 2021). Mean copepod abundance increased across the zone throughout the 2000s and stabilized at near-normal levels during the 2010s (Fig 7A). Copepod abundance increased to above normal in recent years, with larger positive anomalies observed mainly in the NL region (LS, NS, FC, GB) (Fig 7A). In 2021, mean copepod abundance for the zone was above normal for a second consecutive year (Fig. 7A). Over the past two years, copepod abundance decreased from above to near normal on the Seal Island (2J) section, and increased from near to above normal on the shelf portion (3L) of the Flemish Cap section and at the Rimouski monitoring site (4T), and from below to above normal on the eastern and southern Gulf of St. Lawrence (Fig. 8A).

Most abundant non-copepod zooplankton include appendicularians, pteropods, chaetognaths, cladocerans, cnidarians and ctenophores (Maillet et al. 2022, Casault et al. 2020). Mean non-copepod abundance showed little variation throughout the 2000s but increased after that to a maximum in 2016 (Fig. 7B). Abundance has remained above normal since 2015 with mostly positive anomalies in all EPUs (Fig 7B). Over the past two years, the abundance of non-copepods has decreased from above to near normal on the Makkovik Bank (2H) and Seal Island (2J) sections and in the Northwest Gulf of St. Lawrence (4ST), and increased from near to above normal on the 3L portion of the Flemish Cap section, on the eastern (4RS) and southern (4T) Gulf of St. Lawrence, and at the Rimouski monitoring site (4T) (Figure 8B). On the Scotian Shelf where data availability was limited, non-copepod abundance increased from below to near normal at the Halifax 2 monitoring site (Fig. 8B).

Calanus finmarchicus, is a large, energy-rich, widely distributed grazing copepod dominating the mesozooplankton biomass in the North Atlantic (Plank et al. 1997). Broad-scale trend showed an increase in in mean *C. finmarchicus* abundance at the beginning of the 2000s followed by a general decline from approximately 2004 to 2015 with the exception of the high abundance values of 2010 (Fig. 9A). Abundance increased again after the 2015 record low and have since remained near normal including in 2021 (Fig. 9A). However, the negative anomaly for the Scotian Shelf is based on data from the Halifax 2 monitoring site only and abundance in the NL region (LS, NS GB) in 2020 and 2021 has been higher than in previous couple of years (Fig. 9A). Over the past two years, the abundance of *C. finmarchicus* increased from near to above normal on the Bonavista section (3K) and at the Station 27 (3L) and Rimouski (4T) monitoring sites, and from below to near normal on the 3L portion of the Flemish Cap section (Fig. 10A).

Pseudocalanus spp. are highly abundant, widely distributed, small copepods (Pepin et al 2011). They are important prey items often dominating the diet of ecologically important fish species such as herring and capelin (Möllmann et al. 2004, Murphy et al. 2018, Wilson et al. 2018,) and their abundance generally co-vary with that of other numerically abundant small copepod taxa in the region. Mean abundance of *Pseudocalanus* spp. copepods generally increased from 1999 to 2016 before slightly declining to near-normal levels where it has remained since (Fig. 9B). In 2021, *Pseudocalanus* abundance anomalies were positive in all sampled EPUs except the Flemish Cap (Fig. 9B). Over the past two years, the abundance of *Pseudocalanus* spp. has decreased from above to near normal on the Seal Island (2J) section, and from near to below normal in the central and northwest Gulf of St. Lawrence (4RST) while increasing from near to above normal on the 3L portion of the Flemish Cap section, and from below to above normal on the eastern (4RS) and southern (4T) Gulf of St. Lawrence as well as at the Rimouski (4T) and Halifax 2 (4W) monitoring sites (Figure 10B).

3.4. Zooplankton biomass

Mean zooplankton biomass showed a similar overall temporal trend than that of *C. finmarchicus* with an increase in the early 2000s followed by a general decline through to 2015, and by near normal levels over the past six years (Fig. 11). Although the mean zonal anomaly indicate near normal condition for 2021, total zooplankton biomass exhibited spatial variability with positive anomalies across the NL region (LS, NS, FP, GB) and negative anomalies on the Scotian Shelf and the Gulf of St. Lawrence (Fig. 11). Over the past two years, total zooplankton biomass decreased from near to below normal on the eastern (4RS) and northwest (4ST) Gulf of St. Lawrence and at the Halifax 2 monitoring site (4W), and increased from near to above normal on the entire Flemish Cap section (3LM) (Fig. 12).

4. Relationships between ocean climate and biogeochemical oceanographic conditions

Not surprisingly, the correlation matrix indicate several significant correlations between the composite NL climate index and each of its selected components except sea surface temperature (SST) which was positively correlated with air temperature. Significant correlations were also found between the winter NAO index and air temperature (-) and sea ice (+) as well as between bottom temperature and sea ice (-). The positive phase of the winter NAO index is associated with colder climatic conditions in the Newfoundland and Labrador region and, conversely, its positive phase is associated with warmer climate (Colbourne et al. 1994).

The limiting role of nitrate on oceanic primary production (Holt et al. 2012) was highlighted by the positive correlation between nitrate and chlorophyll inventories. The initiation of the spring phytoplankton bloom was correlated with the NL climate and winter NAO indices and, more specifically, with air temperature and sea ice extent. Higher air temperature and absence or faster melting of sea ice favor stratification of ocean's top layer which is critical to phytoplankton buildups in surface waters (Chiswell 2011, Rumyantseva et al. 2019). The negative correlation between bloom initiation and duration suggests that early blooms tend to last longer than late ones. Interestingly, no correlation were found between the magnitude (total production) of the bloom and nitrate or any of the tested physical parameters. Other factors like irradiance and micronutrients such as iron also play an important role in controlling ocean primary productivity (Sigman et al. 2012). Grazing pressure by copepods is another important factor affecting the net primary production in the surface waters (Jagadeesan et al. 2017).

Zooplankton plays a critical role in the oceanic food chain and represents one of the main mechanisms of energy transfer from phytoplankton to higher trophic levels. Their abundance and distribution in marine ecosystems directly or indirectly impact the state of several ecologically and economically important stocks from forage fish to whales (Pendleton et al. 2009, Plourde et al. 2019). In the NW Atlantic, both abundance and biomass of zooplankton are dominated by copepods but other non-copepod organisms such as euphausiids, amphipods, pelagic gastropods, larvaceans, and chaetognaths are also of significant ecological importance.

The abundance of total copepod and *Pseudocalanus* spp., one of the most abundance taxa in NW Atlantic shelf waters, were negatively correlated with integrated chlorophyll biomass. This may seem counterintuitive given the primarily herbivorous feeding mode of *Pseudocalanus* copepeods, but research highlighted the important relative impact of the small copepods on total grazing pressure in the North Atlantic (Morales et al. 1991) which could partly explains the negative relationship between the two.

The positive correlations between zooplankton biomass and the abundance of copepods and *C. finmarchicus* confirmed the important contribution of this group and, more specifically *C. finmarchicus* sto total zooplankton biomass in the NW Atlantic. *C. finmarchicus* was also negatively correlated with bloom initiation. Subadults of *C. finmarchicus* emerge from diapause (winter dormancy stage) in early spring to start producing eggs in surface waters (Head & Pepin 2008, Melle et al. 2014). Egg production in *C. finmarchicus* copepods is positively related to phytoplankton biomass in the North Atlantic (Jónasdóttir et al 2002). It is therefore not surprising to see increased abundance of that species associated to earlier bloom onsets, which is in turn favored by warmer climatic conditions (NL climate, winter NAO, and air temperature indices) and reduced sea ice cover.

5. Biogeochemical oceanographic highlights for 2021

- Spring bloom initiation, duration and magnitude were either near or below the long-term average conditions for the 2003-2020 reference period except for the exceptionally late bloom on the Georges Bank, the longer bloom duration on the Newfoundland Shelf, and the higher spring production (magnitude) on the Scotian Shelf.

- Mean nitrate inventories were near normal for a 3rd consecutive year after the low levels recorded in 2018.

- Mean chlorophyll inventories were near normal for a 2nd consecutive year after the above-normal levels recorded in 2019. The missing data from the cancelled spring surveys certainly contributed to the negative anomalies observed on the Newfoundland Shelf and the Scotian Shelf.

- The abundance of copepods, and more specifically that of the large, energy-rich, *Calanus finmarchicus,* was generally higher in the NL Region compared to the Scotian Shelf and the Gulf of St. Lawrence which was also reflected in the total zooplankton biomass index.

- Mean abundance of small *Pseudocalanus* spp. copepods reamined near normal for a 5th consecutive year in 2021, although it was higher than for the four previous year with positive anomalies in all subregions except for the Flemish Cap.

- Mean abundance of non-copepod zooplankton was above normal for a 7th consecutive year with positive anomalies in all subregions except for the small negative anomaly on the Scotian Shelf.

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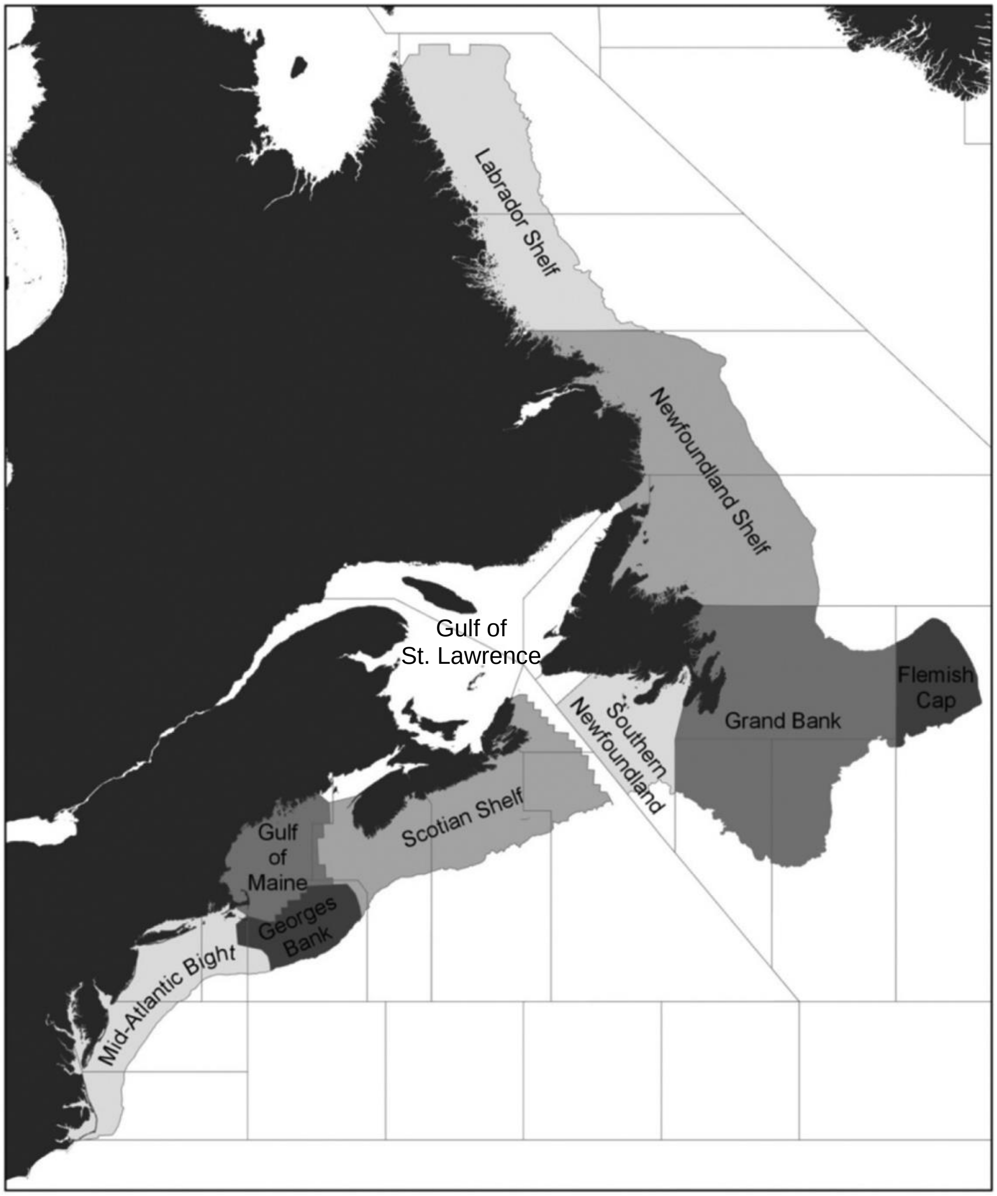

Figure 1. NAFO Ecological Production Units (EPUs) used to summarize biogeochemical oceanographic conditions in the NW Atlantic. The Gulf of St. Lawrence is also used as a grouping unit although it is not an official EPUs. This report do not address conditions in the Gulf of Maine, and Mid-Atlantic Bight EPUs. Figure modified from Koen-Alonso et al. 2019.

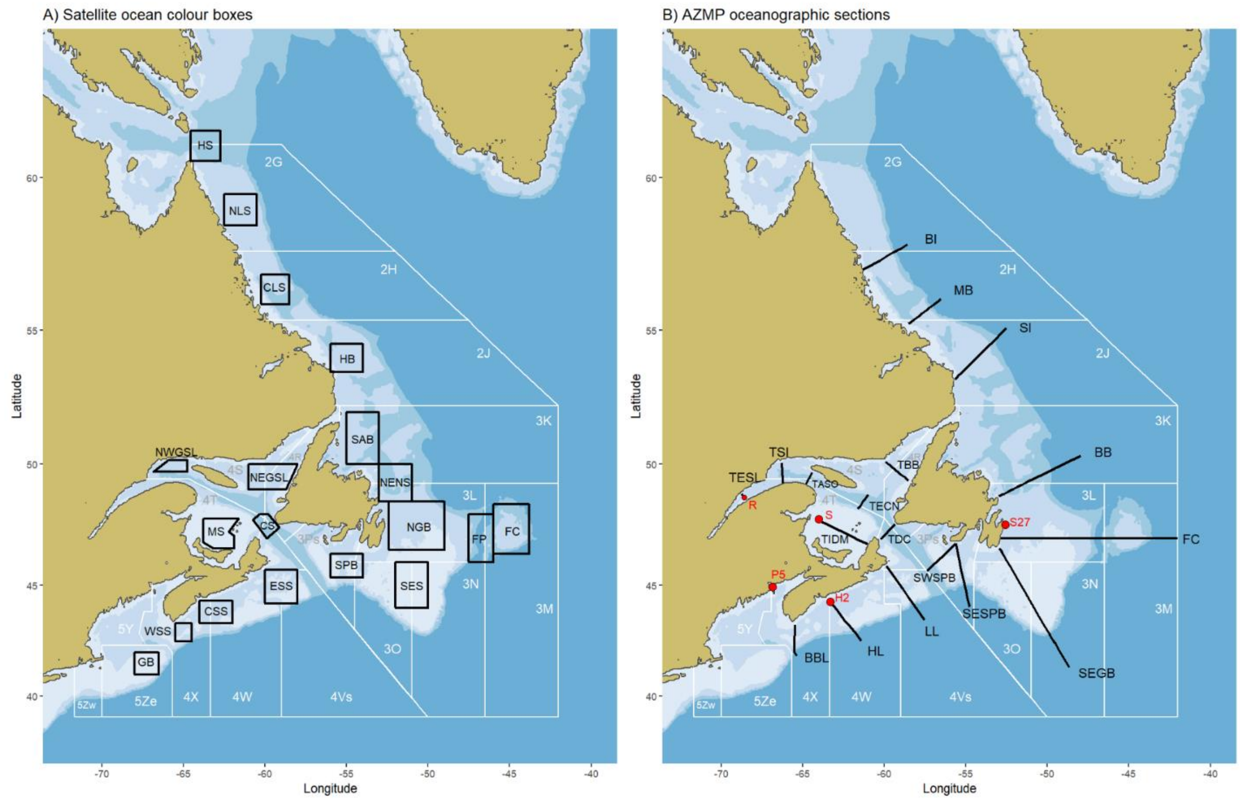

Figure 2. (A) Location of the boxes used to calculate spring bloom indices (initiation duration, magnitude) from satellite Ocean Color imagery: (HS=Hudson Strait, NLS=northern Labrador Shelf, CLS=central Labrador Shelf, HB=Hamilton Bank, SAB=St. Anthony Basin, NENS=northeast Newfoundland Shelf, FP=Flemish Pass, FC=Flemish Cap, NGB=northern Grand Bank, SES=southeast Shoal, SPB=Green-St. Pierre Bank, NEGSL=northeast Gulf of St. Lawrence, NWGSL=northwest Gulf of St. Lawrence, MS=Magdalen Shallows, ESS=eastern Scotian Shelf, CSS=central Scotian Shelf, WSS=western Scotian Shelf, GB=Georges Bank. (B) Location of Atlantic Zone Monitoring Program (AZMP) oceanographic sections (black lines: BI=Beachy Island; MB=Makkovik Bank; SI=Seal Island; BB=Bonavista Bay; FC=Flemish Cap; SEGB=Southeastern Grand Bank; TBB+TCEN+TDC=Eastern Gulf of St. Lawrence; TESL+TSI+TASO=Western Gulf of St. Lawrence; TIDM=Southern Gulf of St. Lawrence; LL=Louisbourg Line; HL=Halifax Line; BBL=Brown Bank Line), and coastal high-frequency monitoring sites (red circles: S27=Station 27; R=Rimouski; S=Shediac Valley; H2=Halifax 2; P5=Prince 5) where biogeochemical data (nitrate, chlorophyll *a,* zooplankton abundance and biomass) were collected.

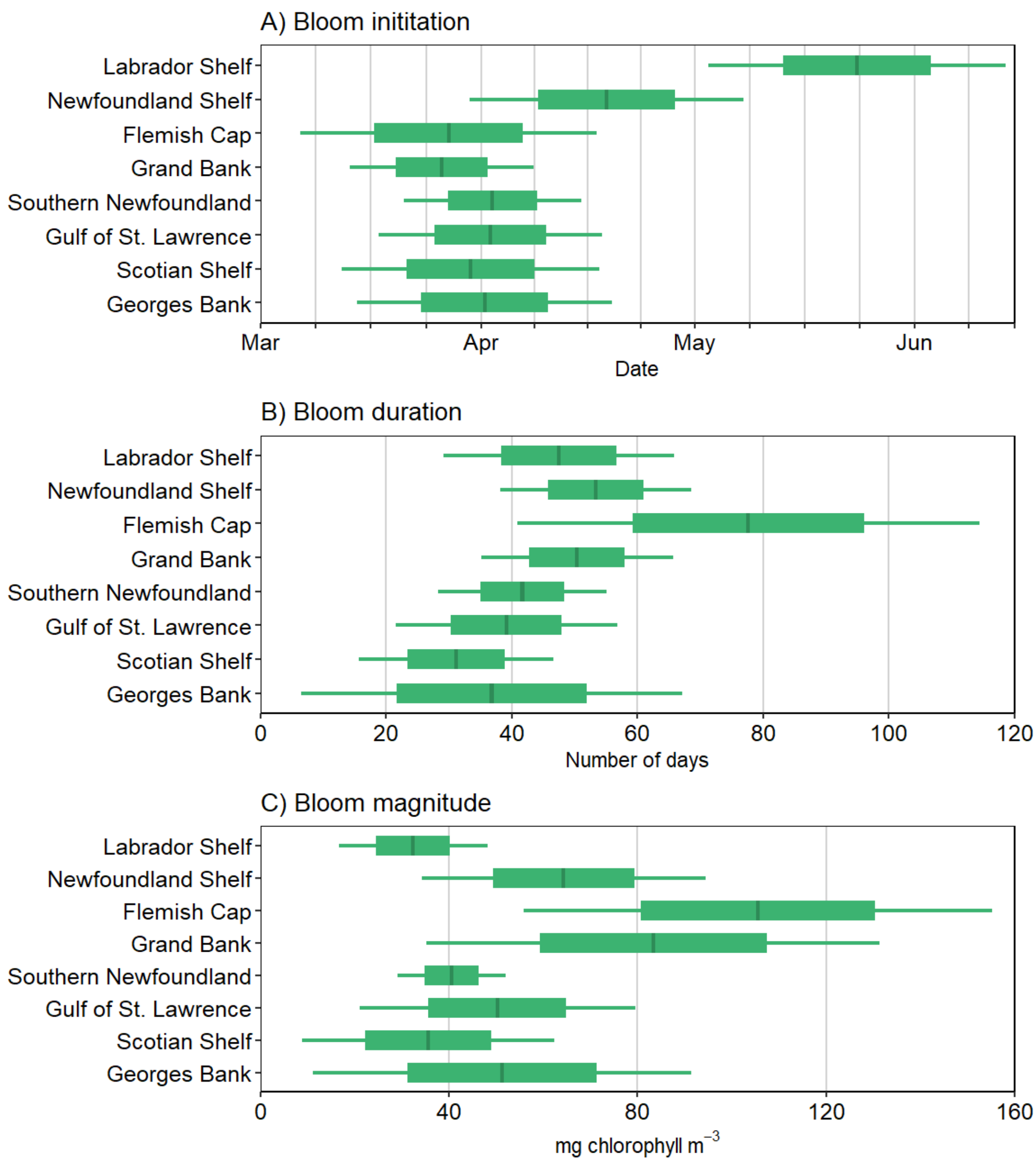

Figure 3. Mean values ± 0.5 SD (rectangles) and ± 1 SD (whiskers) for the spring phytoplankton bloom (A) initiation, (B) duration, and (C) magnitude derived from ocean colour satellite data over the 2003-2020 reference period. The three parameters were calculated for seven NAFO Ecological Production Units (EPUs: Labrador Shelf, Newfoundland Shelf, Flemish Cap, Grand Bank, Southern Newfoundland, Scotian Shelf, and Georges Bank) and for the Gulf of St. Lawrence. See Fig. 1 for EPUs locations.

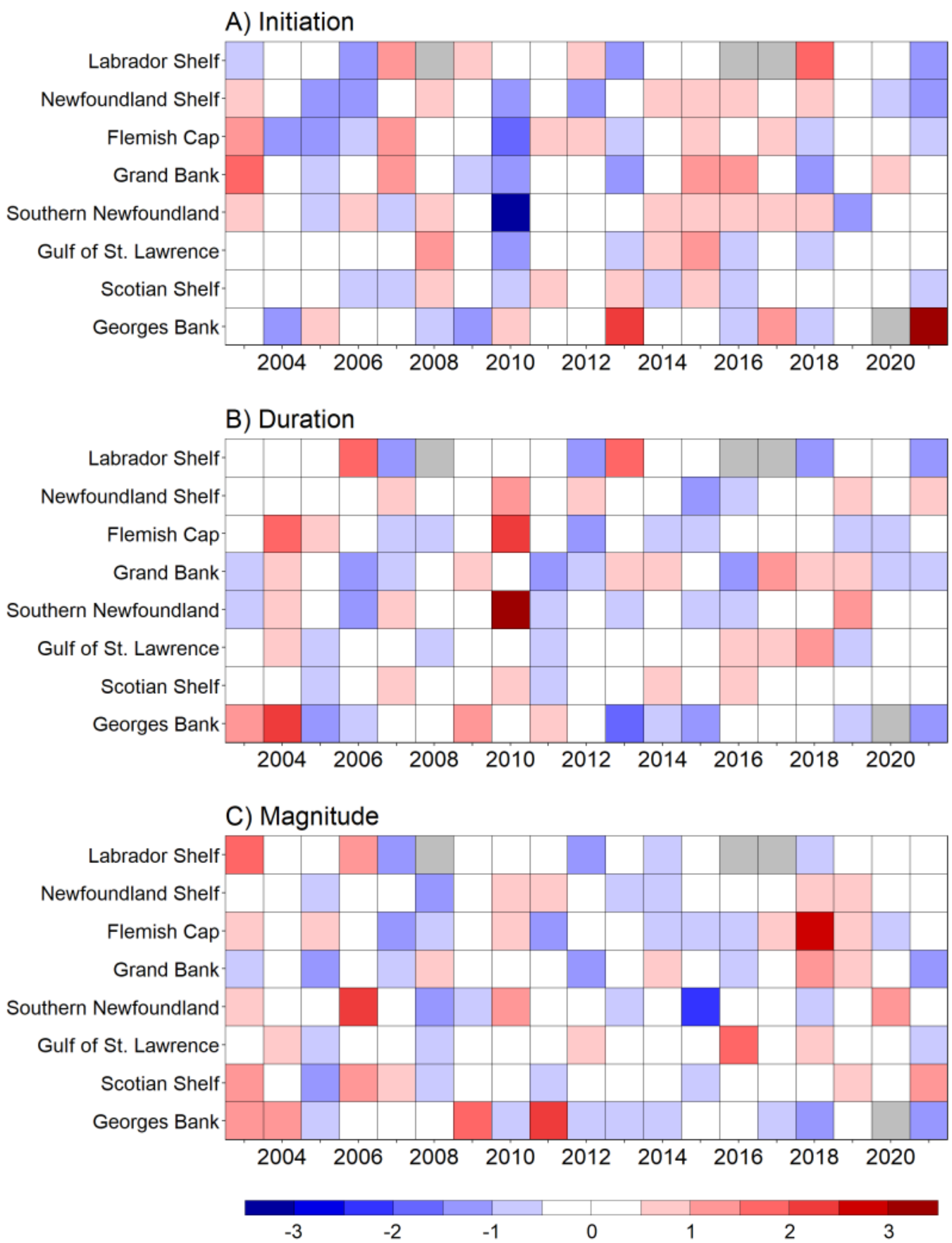

Figure 4. Annual standardized anomaly scorecards for the spring phytoplankton bloom (A) initiation, (B) duration, and (C) magnitude for seven NAFO Ecological Production Units (EPU) and for the Gulf of St. Lawrence (GSL). Standardized anomalies were calculated for each oceanographic section and high-frequency monitoring site using a 2003-2020 reference period and averaged over geographical grouping units (EPUs or GSL). Red (blue) cells indicate later (earlier) bloom initiation, longer (shorter) bloom duration, or higher (lower) bloom magnitude relative to the 2003-2020 reference period. White cells indicate near-normal conditions, i.e. ± 0.5 SD from the mean for the reference period. Grey cells indicate years for which limited data availability did not permit index calculation. Regions are listed from North (top) to south (bottom). See Fig. 1 for the location of geographical grouping units.

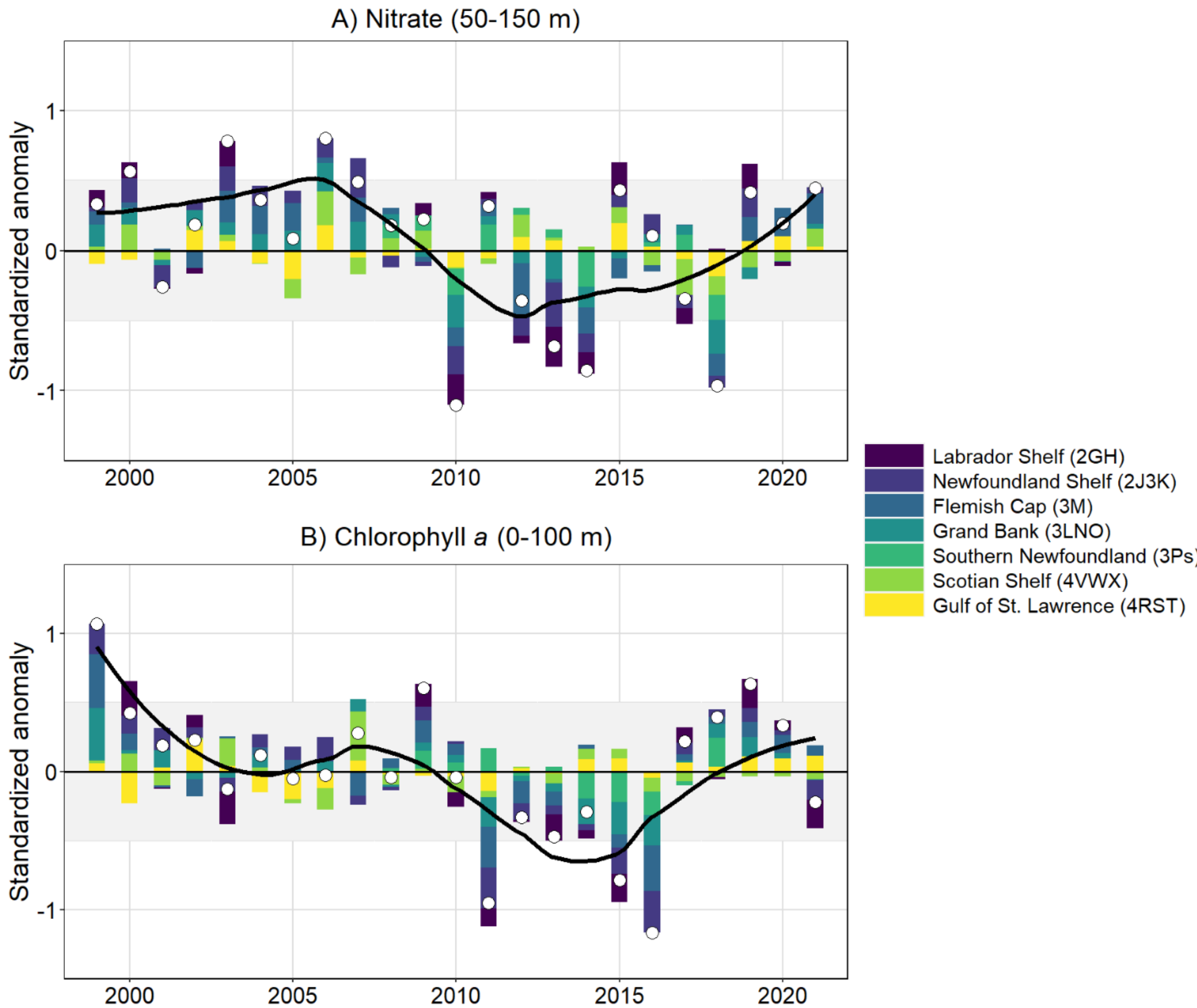

Figure 5. Annual anomaly time series of (A) 50-150 m integrated nitrate, and (B) 0-100 m integrated chlorophyll-*a* inventories in six NAFO Ecological Production Units (EPU) and in the Gulf of St. Lawrence (GSL). Standardized anomalies were calculated for each oceanographic section and high-frequency monitoring site using a 1999-2020 reference period and averaged over geographical grouping units (EPUs or GSL). White circle indicate the mean annual anomaly for the Northwest Atlantic (NWA). Colour bars indicate the relative contribution of each grouping unit to the mean anomaly. The black line is a loess regression fitted to the annual mean anomalies that summarizes the broad-scale temporal trend observed across the NWA. See Figs. 1 & 2B for the location of geographical grouping units, oceanographic sections and high-frequency monitoring sites.

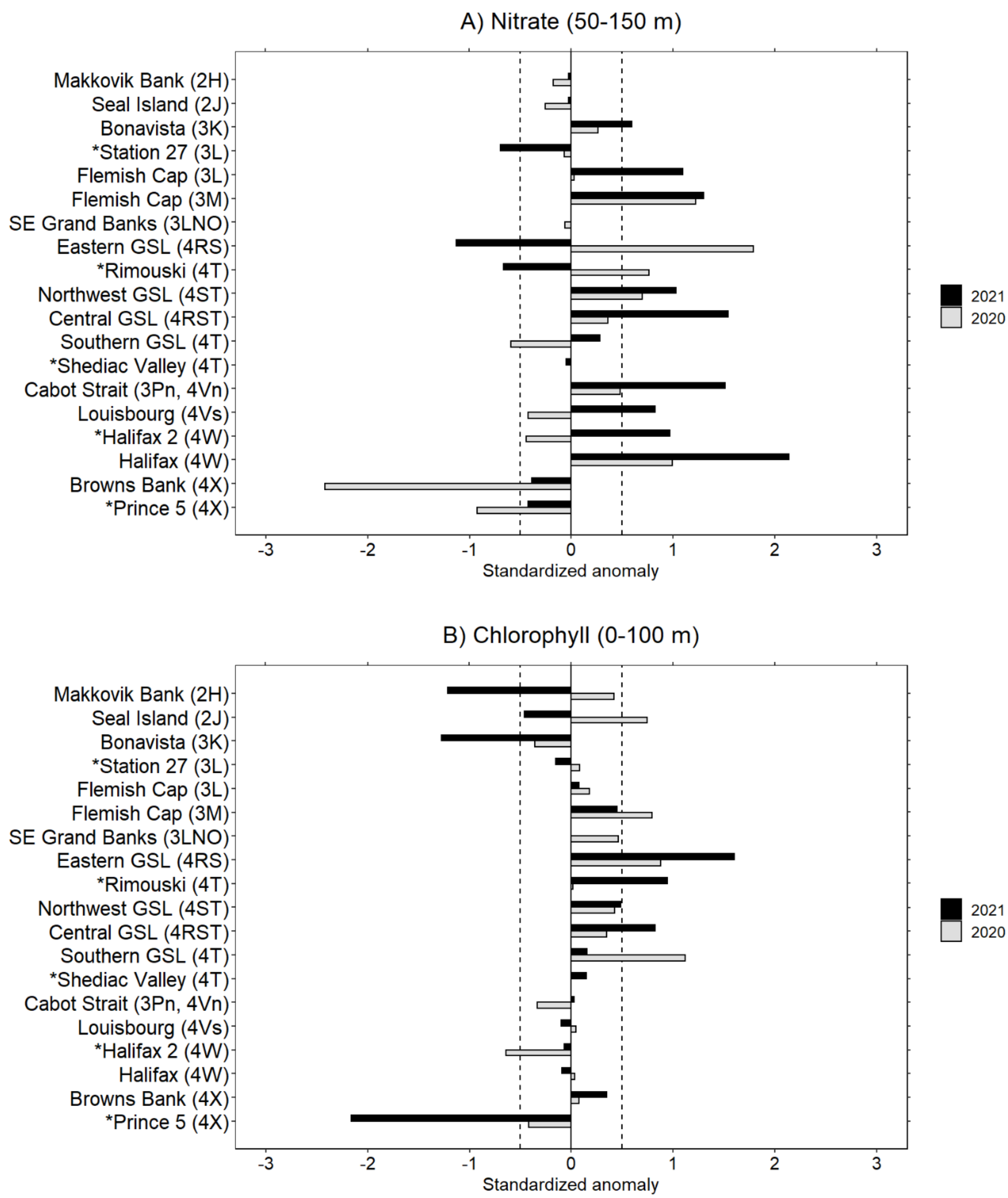

Figure 6. Comparison between 2020 and 2021 annual anomalies of (A) 50-150 integrated nitrate, and (B) 0-100 m integrated chlorophyll-*a* inventories for each AZMP oceanographic section and high-frequency monitoring site sampled by the AZMP. Anomalies were calculated based on a 1999-2020 reference period. Anomalies within ±0.5 SD (vertical dashed lines) are considered to represent near-normal conditions. Sampling locations are listed from north (top) to south (bottom). Asterisks (*) indicate high-frequency monitoring sites. See Figure 2B for oceanographic sections and high-frequency monitoring sites location.

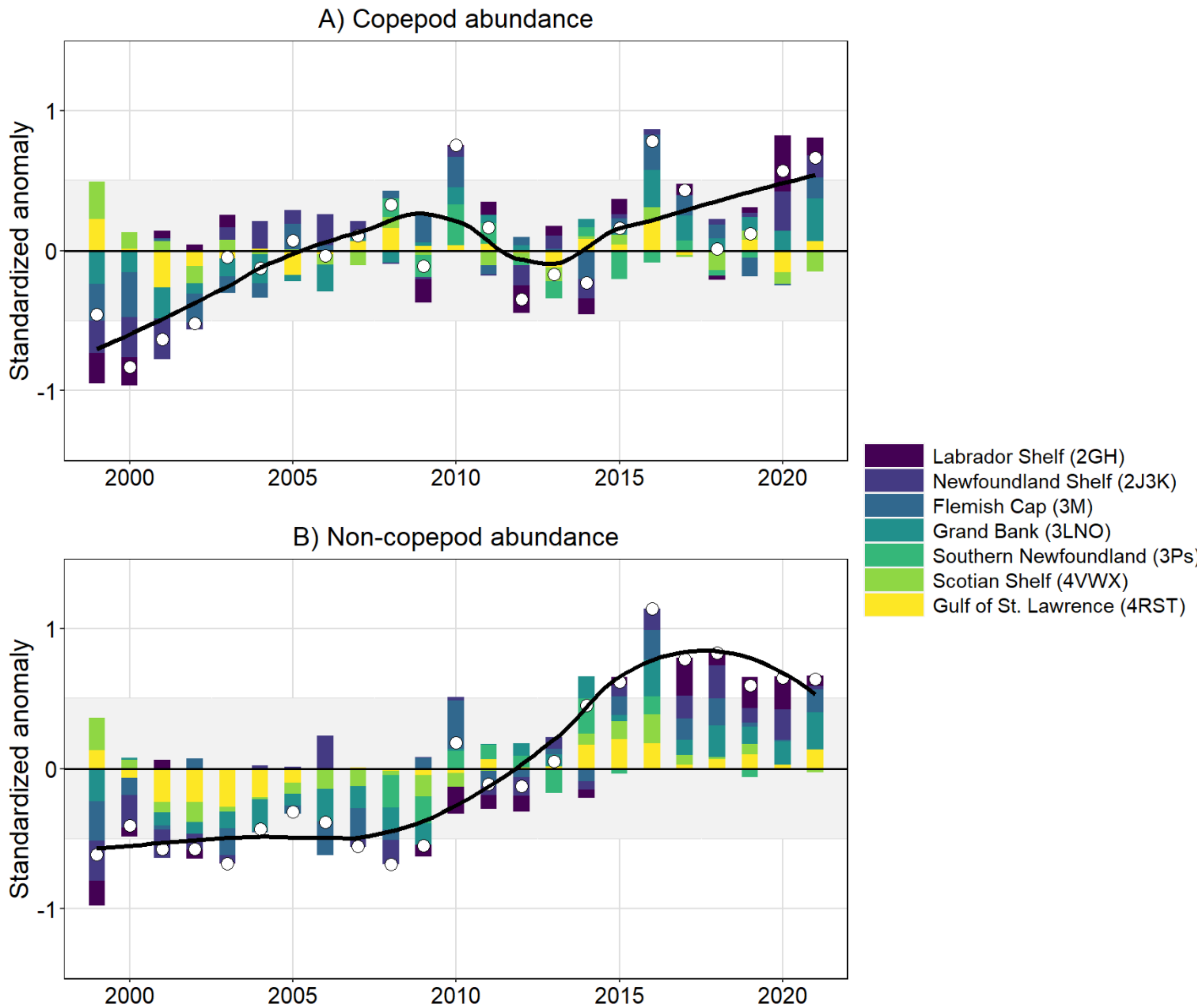

Figure 7. Anomaly time series of (A) copepod, and (B) non-copepod zooplankton abundance (ind. · m^{-2}) in six NAFO Ecological Production Units (EPU) and in the Gulf of St. Lawrence (GSL). Standardized anomalies were calculated for each oceanographic section and high-frequency monitoring site using a 1999-2020 reference period and averaged over geographical grouping units (EPUs or GSL). White circle indicate the mean annual anomaly for the Northwest Atlantic (NWA). Colour bars indicate the relative contribution of each grouping unit to the mean anomaly. The black line is a loess regression fitted to the annual mean anomalies that summarizes the broad-scale temporal trend observed across the NWA. See Figs. 1 & 2B for the location of geographical grouping units, oceanographic sections and high-frequency monitoring sites.

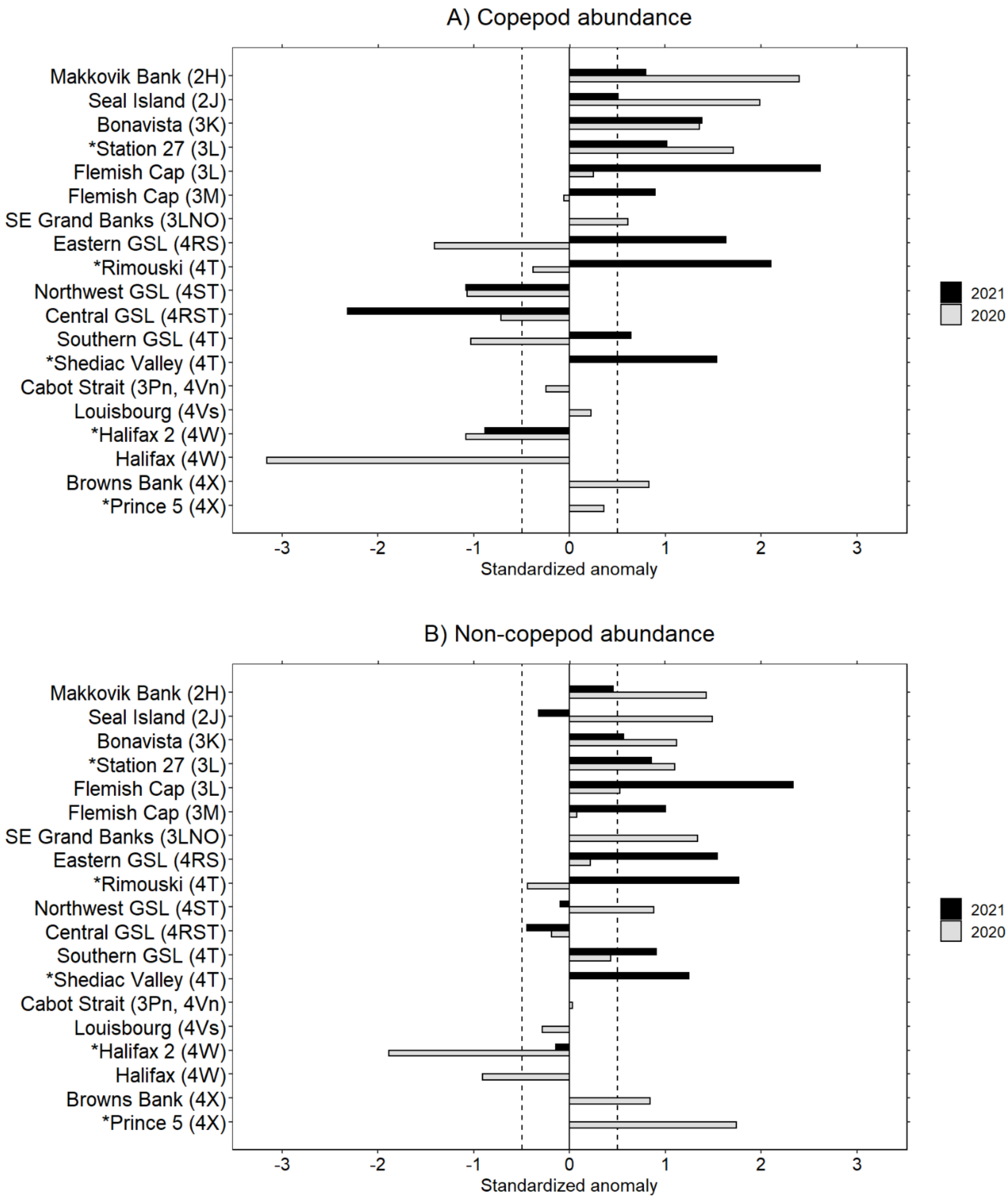

Figure 8. Comparison between 2020 and 2021 annual anomalies for copepod (A), and non-copepod (B) abundance (ind. · m^{-2}) for each AZMP oceanographic section and high-frequency monitoring site sampled by the AZMP. Anomalies are calculated based on a 1999-2020 reference period. Anomalies were calculated based on a 1999-2020 reference period. Anomalies within ±0.5 SD (vertical dashed lines) are considered to represent near-normal conditions. Sampling locations are listed from north (top) to south (bottom). Asterisks (*) indicate high-frequency monitoring sites. See Figure 2B for oceanographic sections and high-frequency monitoring sites location.

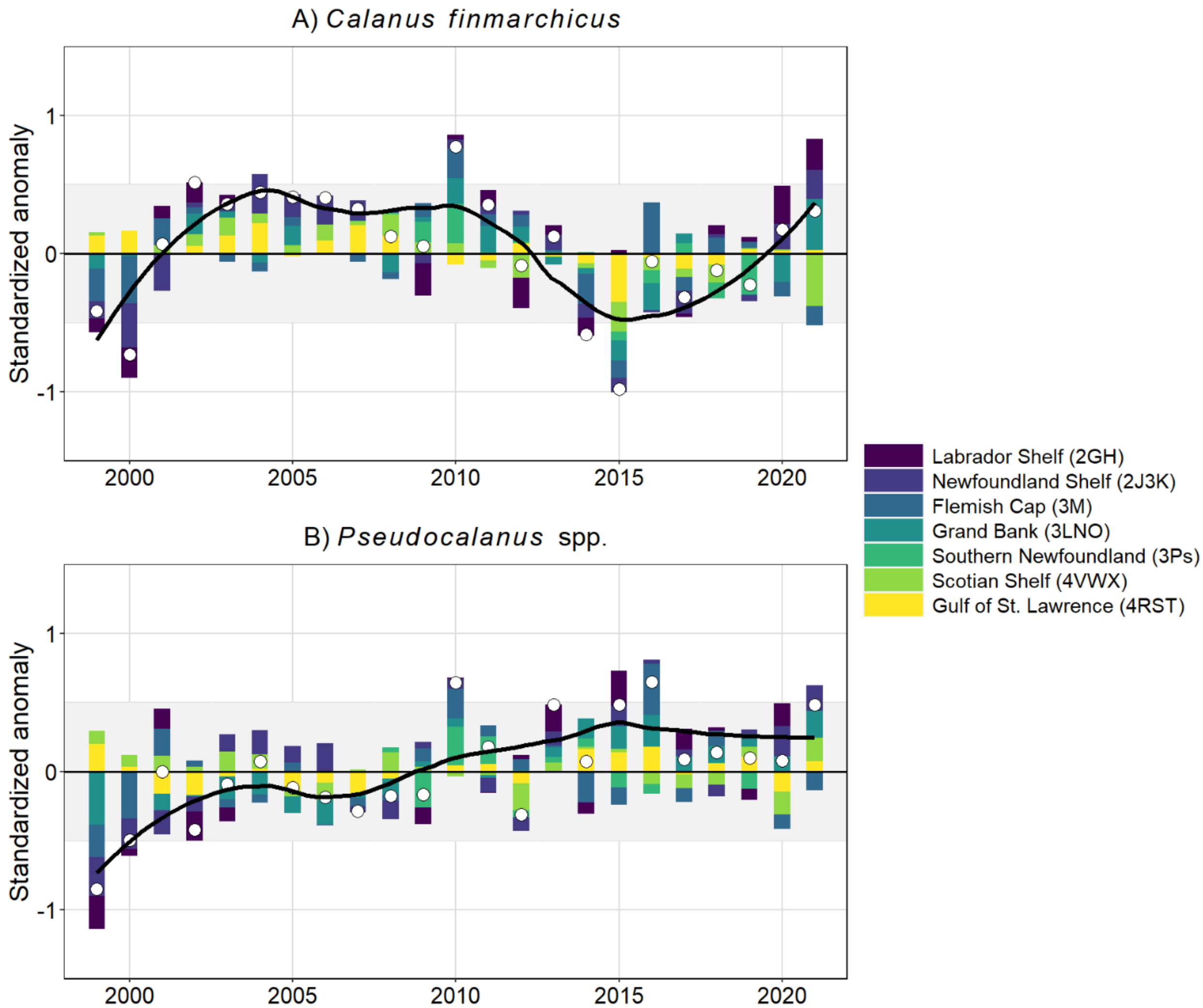

Figure 9. Annual anomaly time series of (A) *Calanus finmarchicus* and (B) *Pseudocalanus* spp. copepod abundance (ind. · m^{-2}) in six NAFO Ecological Production Units (EPU) and in the Gulf of St. Lawrence (GSL). Standardized anomalies were calculated for each oceanographic section and high-frequency monitoring site using a 1999-2020 reference period and averaged over geographical grouping units (EPUs or GSL). White circle indicate the mean annual anomaly for the Northwest Atlantic (NWA). Colour bars indicate the relative contribution of each grouping unit to the mean anomaly. The black line is a loess regression fitted to the annual mean anomalies that summarizes the broad-scale temporal trend observed across the NWA. See Figs. 1 & 2B for the location of geographical grouping units, oceanographic sections and high-frequency monitoring sites.

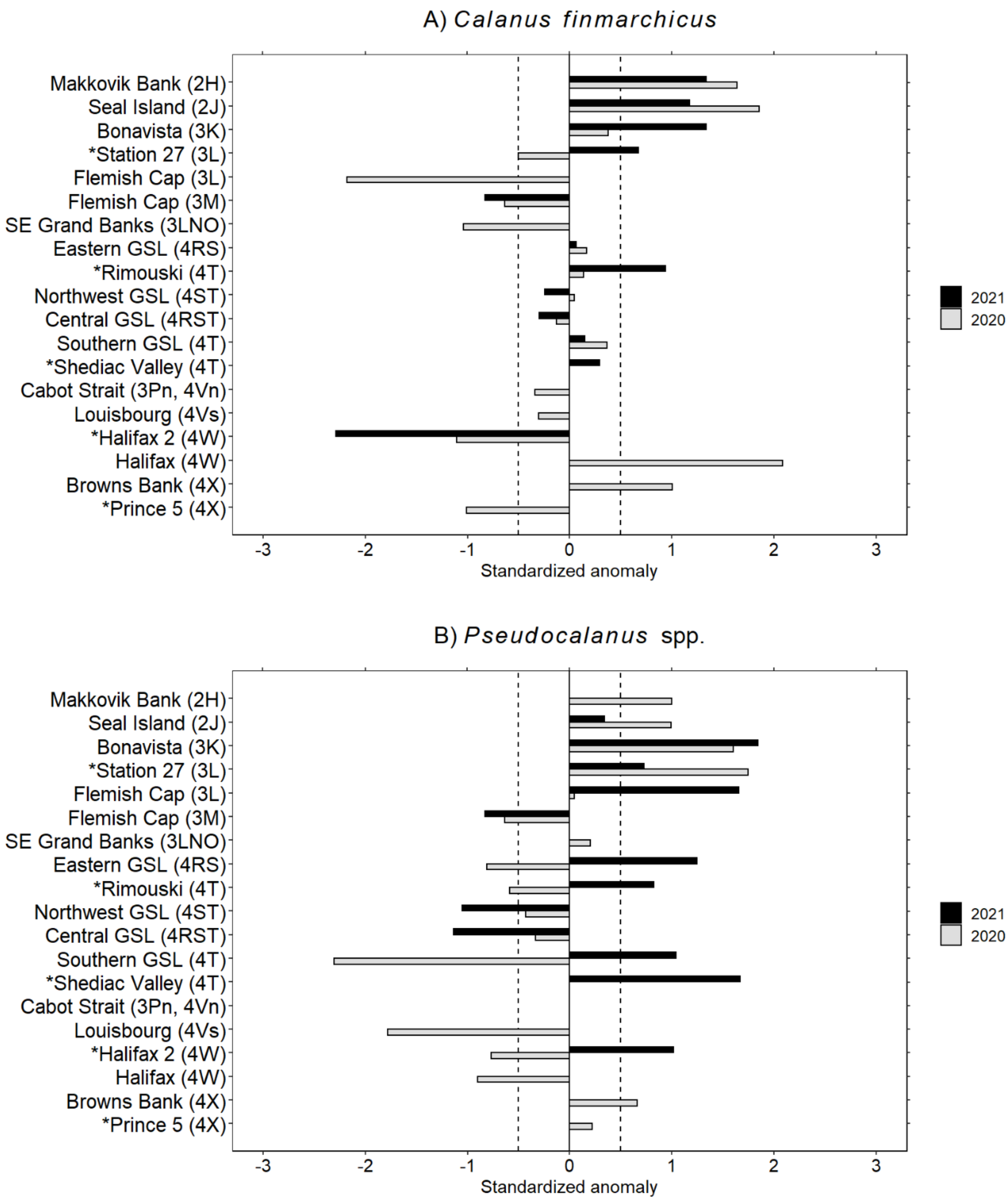

Figure 10. Comparison between 2020 and 2021 annual anomalies for (A) *Calanus finmarchicus*, and (B) *Pseudocalanus* spp. copepod abundance (ind. · m^{-2}) for each AZMP oceanographic section and high-frequency monitoring site sampled by the AZMP. Anomalies were calculated based on a 1999-2020 reference period. Anomalies within ±0.5 SD (vertical dashed lines) are considered to represent near-normal conditions. Sampling locations are listed from north (top) to south (bottom). Asterisks (*) indicate high-frequency monitoring sites. See Figure 2B for oceanographic sections and high-frequency monitoring sites location.

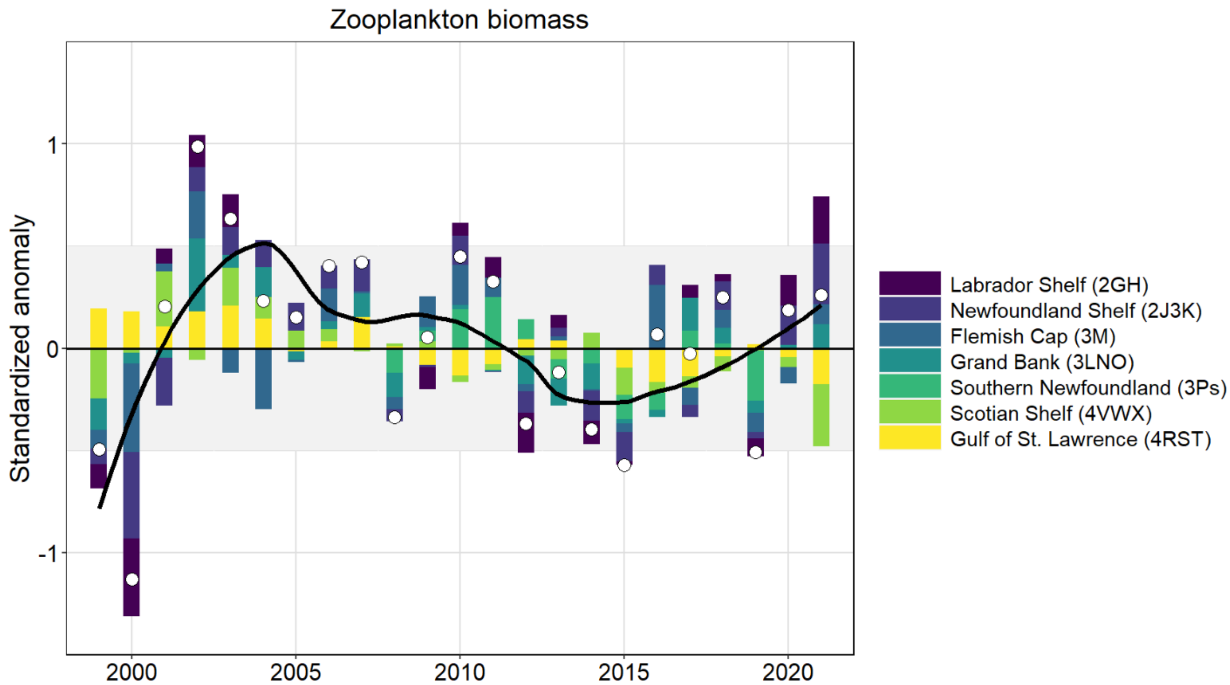

Figure 11. Annual anomaly time series of zooplankton biomass (g dry weight · m^{-2}) in six NAFO Ecological Production Units (EPU) and in the Gulf of St. Lawrence. Standardized anomalies were calculated for each oceanographic section and high-frequency monitoring site using a 1999-2020 reference period and averaged over geographical grouping units (EPUs or GSL). White circle indicate the mean annual anomaly for the Northwest Atlantic (NWA). Colour bars indicate the relative contribution of each grouping unit to the mean anomaly. The black line is a loess regression fitted to the annual mean anomalies that summarizes the broad-scale temporal trend observed across the NWA. See Figs. 1 & 2B for the location of geographical grouping units, oceanographic sections and high-frequency monitoring sites.

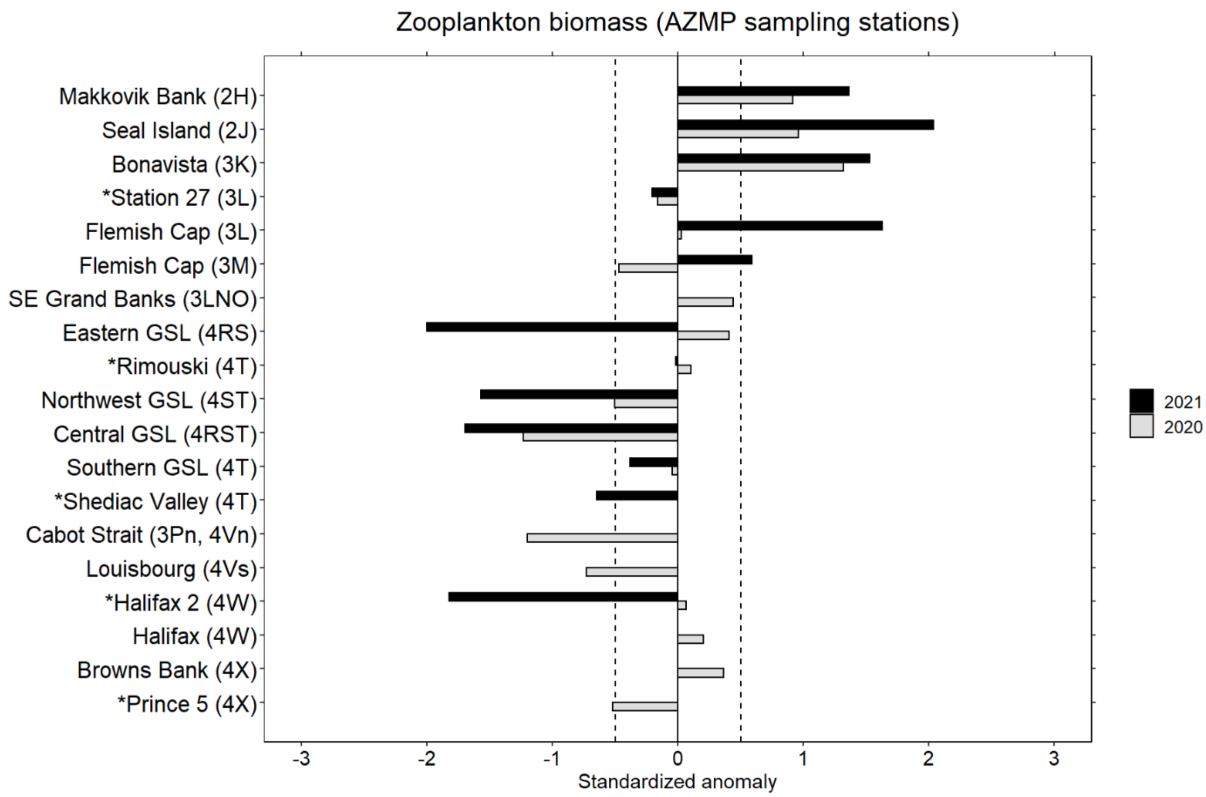

Figure 12. Comparison between 2020 and 2021 annual anomalies for zooplankton biomass (g · dry weight · m^{-2}) for each AZMP oceanographic section and high-frequency monitoring site sampled by the AZMP. Anomalies are calculated based on a 1999-2020 reference period. Anomalies were calculated based on a 1999-2020 reference period. Anomalies within ±0.5 SD (vertical dashed lines) are considered to represent near-normal conditions. Sampling locations are listed from north (top) to south (bottom). Asterisks (*) indicate high-frequency monitoring sites. See Figure 2B for oceanographic sections and high-frequency monitoring sites location.

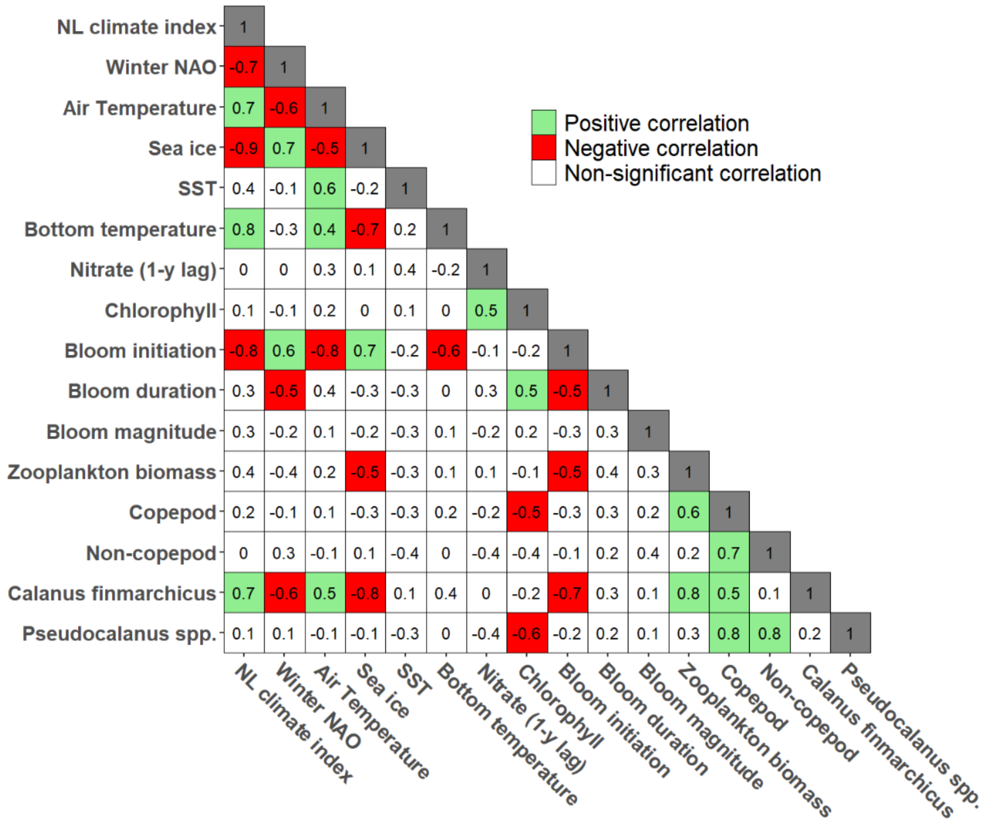

Figure 13. Correlation matrix summarizing the relationships between physical (Newfoundland and Labrador climate index, winter North Atlantic Oscillation [NAO] index, air temperature, sea ice cover, sea surface temperature [SST], and bottom temperature), and biogeochemical (phytoplankton spring bloom initiation, duration, and magnitude; integrated deep nitrate [50-150 m]; integrated chlorophyll *a* [0-100 m]; abundance of copepod, non-copepod, *Calanus finmarchicus*, *Pseudocalanus* spp.; zooplankton biomass) indices for the Southern Newfoundland, Grand Bank, Flemish Cap, Newfoundland Shelf, and Labrador Shelf EPUs during the 1999-2021 period. Green cells indicate significant positive correlation, red cells indicate significant negative correlation, and white cells indicate non-significant correlations. Numbers in cells are Pearson correlation coefficients (r). Significance level for Pearson correlation tests was α=0.05.