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Biogeochemical oceanographic conditions in the Northwest Atlantic (NAFO subareas 2-3-4) during 2020

by

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Abstract

Biogeochemical variables collected in 2020 from coastal high-frequency monitoring stations and seasonal sampling of standard oceanographic sections covering NAFO Subareas 2-4 are presented and referenced to earlier periods when available. We review spatial and inter-annual variations in phytoplankton spring bloom indices as well as vertically integrated nitrate and chlorophyll *a*, zooplankton abundance, and zooplankton biomass inventories collected by the Atlantic Zone Monitoring Program (AZMP) and ships of opportunity in 2020. Spring bloom timing, duration, and magnitude were mostly near normal across the Canadian NW Atlantic except for the early and exceptionally long bloom observed on the Georges Bank. In general, nitrate and chlorophyll inventories remained near or above normal on the Newfoundland and Labrador shelves, Flemish Cap, Grand Bank and Gulf of St. Lawrence, and below to near normal on the Scotian Shelf. The abundance of copepod and non-copepod zooplankton increased or remained high on the Newfoundland and Labrador shelves and the Grand Bank, but generally decreased in the Gulf of St. Lawrence and on the Scotian Shelf. The abundance of large *Calanus finmarchicus* copepods increased on the northern Newfoundland and Labrador shelves and western Scotian Shelf, and decreased on the Flemish Cap and the Grand Bank. The abundance od small *Pseudocalanus* spp. copepods increased on the Newfoundland and Labrador shelves, but drastically decreased almost everywhere else. Trends in total zooplankton biomass indicated an increase for the Newfoundland and Labrador shelves, and an overall decrease for the Gulf of St. Lawrence compared to 2019.

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1. Introduction

Here, we review the biogeochemical oceanographic conditions in Northwest (NW) Atlantic shelf waters within NAFO Subareas 2, 3 and 4. We present results collected in 2020, and reference earlier periods where data are available. Satellite ocean colour data in addition to directed seasonal sampling of oceanographic sections by the Atlantic Zone Monitoring Program (AZMP) and at coastal high-frequency monitoring stations by ships of opportunity provided reasonable spatial and temporal series coverage. Annual collection of standard variables (nutrients, chlorophyll, zooplankton abundance, and zooplankton biomass) since 1999 allows to compare patterns of variation and trends among ecologically relevant biogeochemical indices in the NW Atlantic. We use NAFO Ecological Production Units (EPUs) and the Gulf of St. Lawrence as grouping units to summarise biogeochemical oceanographic 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 2019 and earlier years can be found in Maillet et al. (2019), Casault et al. (2020), Galbraith et al. (2020), Blais et al. (2021), Cyr et al. (2021), Hebert et al. (2021), Yashayaev et al. (2021).

2. Methods

Surface chlorophyll *a* concentration across the NW Atlantic was obtained from ocean colour observations with 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., 2003-2020. A shifted Gaussian function of time was used to calculate spring bloom initiation, duration, and magnitude (total production) for selected areas (see Fig. 2A) following a method adapted from Zhai et al. (2011).

Collection of standard AZMP variables (integrated nitrate [50-150 m] and chlorophyll [0-100 m] inventories, total copepod, non-copepod, *Calanus finmarchicus* and *Pseudocalanus* spp. abundance, and total zooplankton biomass) followed protocols outlined in Mitchell *et al*. (2002). Observations for 2020 and earlier years presented in this document are based on seasonal surveys conducted in spring, summer and fall (typically March through December) along the standard AZMP oceanographic sections and coastal high-frequency-monitoring stations. The high-frequency monitoring stations are typically sampled at twice monthly to monthly intervals during the ice-free period of the year. The location of the standard oceanographic sections and high-frequency monitoring stations are shown in Fig. 2B. Standardized anomalies were used to summarize the spatial and temporal trends observed for the variables selected to represent the state of nutrients and lower trophic levels in the NW Atlantic. Annual standardized anomalies were calculated for each 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). Annual standardized anomalies for the spring bloom phenology (bloom initiation, duration, and magnitude) were calculated on non-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 stations) fitted to log transformed data (ln (x+1)). The result of this standardization yields 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 long-term reference period. The reference periods used are 2003-2020 for the satellite-derived spring bloom indices, and 1999-2020 for AZMP biogeochemical indices. In 2020, 5 years were added to the reference period used in anterior version of this report (1999-2015). Extending reference period for the relatively short AZMP time series allow to better capture the significance of the departure of a given index relative to its long-term natural variation. Although changing the reference period may result in minor changes in the values and sometimes the sign (positive or negative), of the anomalies presented in previous reports, it had little effect on the overall spatial and temporal trends.

Anomaly values within ± 0.5 SD from the climatological mean are representative of near normal conditions. Positive anomalies > 0.5 SD indicate conditions above the climatological mean. Negative anomalies < 0.5 SD indicate conditions below the climatological mean. Annual standardized anomalies of each oceanographic sections and high-frequency monitoring stations were averaged over NAFO EPUs (Labrador Shelf, Newfoundland Shelf, Flemish Cap, Grand Bank, Southern Newfoundland, Scotian Shelf, and Georges Bank) and the Gulf of St. Lawrence to provide an estimate of the overall oceanographic trends within each ecological unit. The standard AZMP variables selected were: spring bloom initiation (day of year), duration (days) and magnitude (mg m^{-3}); 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 in the chemical and biological in situ observations 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 stations and dividing the results by the number of sections and stations included in the calculation.

We produced a correlation matrix (Pearson) 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 the 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.

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 starts in late March to early April from Georges Bank to 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 ~1 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 of the spring bloom in the NW Atlantic shelf waters generally occurred earlier in the 2000s (mostly negative anomalies) compared to the 2010s (mostly positive anomalies) although near-normal timing was observed in most regions since 2019 with the exception of a particularly early bloom on the Georges Bank in 2020 (Fig. 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 and the Newfoundland and the Labrador shelves (Fig. 3B). Bloom duration varies more in the south on the Georges Bank (~20-45 d), and on the Flemish Cap where blooms tend to be longer (~60-95 d) than in other regions (Fig. 3B). Bloom duration varied yearly with no clear long-term spatial or temporal trends throughout the time series (Fig. 4B). The near or slightly below normal duration of the spring bloom in 2020 contrasted with the longer blooms (positive anomalies) observed in several regions in 2018 and 2019 (Fig. 4B). The exception for 2020 was the time series record high duration recorded on the Georges Bank.

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 the Georges Bank to the Southern Newfoundland, and maximum at mid-latitudes on the Grand Bank, the Flemish Cap and Newfoundland Shelf (Fig. 3C). High surface primary production in these latter regions is likely explained by the extended duration (Flemish Cap) and high intensity (Grand Bank and Newfoundland Shelf) of the spring bloom.
Spring bloom production remained mostly below or near normal across the NW Atlantic between 2011 and 2016 but increased to above normal levels in most regions in 2018 ad 2019 (Fig. 4C). This recent increase in spring bloom production aligns with the return to slightly earlier and longer blooms during the same period (Fig. 4A-C). Spring bloom production was near or above normal across the NW Atlantic in 2020 with the exception of the negative anomaly recorded on the Flemish Cap.

3.2. Nitrate and chlorophyll *a*

Integrated (50-150 m) nitrate inventory anomalies shifted from mostly positive in all EPUs during the 2000s, to mostly negative during the 2010s (Fig. 5A). Mean anomalies for the NW Atlantic generally showed no strong departures from the climatology except for 2010 and 2018 where anomalies reached up to one SD below the long-term average conditions. Nitrate inventories show an overall increasing trend since the time series record-low observed in 2010, but are still below the high levels observed in the mid-2010s (Fig. 5A). Over the past two years, nitrate inventories were mainly near to above normal in the Gulf of St. Lawrence (NAFO Div. 4RST) and from the Grand Bank and Flemish Cap to the north (2HJ3KLMNO), and below to near normal on the Scotian Shelf (4VWX) (Fig. 6A). In 2020, notable increases compared to the previous year were observed at Station 27 (3L) and on the Eastern (4RS) and Central Gulf of St. Lawrence (4RST), as well as along the Halifax section (4W), while marked decreases were recorded for the Makkovik Bank (2H), Seal Island, southern Gulf of St. Lawrence, and Browns Bank sections (Fig. 6A).

Integrated (0-100 m) chlorophyll *a* inventories show a similar broad-scale trend to that of nitrate with mostly positive anomalies throughout the 2000s, followed by a decrease to negative anomalies during the early and mid-2010s (Fig. 5B). The positive anomalies observed since 2017 aligns with the return of nitrate inventories to near normal levels since 2015. 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). Over the past two years, chlorophyll inventories were mainly near to above normal in the Gulf of St. Lawrence (NAFO Div. 4RST) and from the Grand Bank and Flemish Cap to the north (2HJ3KLMNO), and near normal on the Scotian Shelf (4VWX) (Fig. 6B). In 2020, notable increases compared to the previous year were observed along the entire Flemish Cap section (3LM), while marked decreases we recorded at the Station 27 (3L) and Rimouski (4T) high-frequency monitoring stations and in the northwest Gulf of St. Lawrence (4ST) (Fig 6B).

3.3 Zooplankton abundance

Copepods numerically dominate zooplankton assembles in the North Atlantic (Maillet et al. 2019, Casault et al., 2020, Blais et al. 2021). The abundance of copepods steadily increased across the Canadian NW Atlantic throughout the 2000s. It then slightly decreased in the early 2010s, before increasing again during the late 2010s (Fig. 7A). A marked increase in total copepod abundance was recorded in 2020 compared to the previous year on the Newfoundland (2J3K) and Labrador (2H) shelves as well as at Station 27 (3L) (Fig. 8A). These observations contrast with the radical shift from positive to negative anomalies observed in the Gulf of St. Lawrence (4RST) and on the central Scotia Shelf (4W) during the same period (Fig. 8A).

Most abundant non-copepod zooplankton include amphipods, euphausiids, appendicularians, pteropods, chaetognaths, cladocerans, cnidarians and ctenophores (Maillet et al. 2018, Casault et al. 2020). The abundance of non-copepod zooplankton remained stable throughout the 2000s, and rapidly increased in the early the 2010s to stabilize at a high level since ~2017 (Fig. 7B). Abundance has remained high in 2020 on the Newfoundland (2J3K) and Labrador (2H) shelves as well as on the Southeastern Grand Bank (3LNO) and at Station 27 (3L), but decreased compared to 2019 on the central (4RST) and southern (4T) Gulf of St. Lawrence, an especially in the Cabot Strait (3Pn4Vn) and on the eastern (4Vs) and central (4W) Scotian Shelf. In contrast, non-copepod abundance increased from near normal in 2019 to above normal in 2020 on the western Scotian Shelf and in the Bay of Fundy (Fig. 8B).

Calanus finmarchicus, is a large, high-energy content, widely distributed grazing copepod dominating the mesozooplankton biomass in the North Atlantic (Plank et al. 1997). Broad-scale trend shows an increase in *C. finmarchicus* abundance followed by a gradual decline through to a record low in 2015 with the exception of the high level observed in 2010 (Fig. 9A). Abundance increased during the late 2010s to a positive mean anomaly in 2020 for the first time in 7 years (Fig. 9A). *C. finmarchicus* abundance showed an important increase in 2020 compared to 2019 on the Newfoundland (2J3K) and Labrador (2H) shelves as well as on the western Scotian Shelf (4WX) (Fig. 10A). In contrast, notable declines were observed on the Flemish Cap (3M), the Grand Bank (3LNO), and at the Halifax 2 (4W) and Prince 5 (4X) high-frequency coastal monitoring stations respectively located on the central Scotian Shelf and in the Bay of Fundy (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,). Broad-scale trend show an overall increase in the abundance of *Pseudocalanus* spp. copepods between 1999 and 2016 followed by a slight decrease in the late 2010s (Fig. 11B). There was important changes in the distribution of *Pseudocalanus* spp. over the past 2 years characterized by an important increase in the abundance on the Newfoundland (2J3K) and Labrador (2H) shelves in 2020 compared to 2019 concurrent with a generalized decline in abundance across the Gulf of St. Lawrence and the Scotian Shelf (Fig. 12B). Declines were especially important in the southern Gulf of St. Lawrence (4T), in the Cabot Strait (3Pn4Vn) and on the eastern Scotian Shelf (4Vs) (Fig. 12B).

3.4. Zooplankton biomass

Broad-scale trend in zooplankton biomass show a rapid increase in the early 2000s followed by a gradual decline through to 2015, and moderate increase over the past 5 years with the exception of the 2019 low mean anomaly (Fig. 11). Biomass increased on the Newfoundland (2J3K) and Labrador (2H) shelves and the southeastern Grand Bank (3LNO) in 2020compared to 2019, and decreased on the northwest Gulf of St. Lawrence (4ST) and in the Bay of Fundy (4X) during the same period (Figure 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 on the Newfoundland and Labrador climate and, conversely, its positive phase is associated with warmer climate (Colbourne et al. 1994).

Nitrate and chlorophyll inventories were positively correlated, outlining the limiting role of nitrate in oceanic primary production (Holt et al. 2012). The initiation and duration of the spring phytoplankton bloom were both correlated with the NL climate and winter NAO indices but also, more specifically with air temperature and sea ice extent. Higher air temperature and absence or faster melting of sea ice and associated freshwater input favor stratification of ocean's top layer which is critical to phytoplankton buildups in surface waters (Chiswell 2011, Rumyantseva et al. 2019). Early onset allows for the bloom to develop over a longer period as outlined by the negative correlation between bloom initiation (negative anomaly=early onset) and duration. 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).

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). 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. Although this may seem counterintuitive given the primarily herbivorous feeding mode of *Pseudocalanus* copepeods, but it has been shown that high copepod abundance increases grazing pressure on phytoplankton standing stock (Jagadeesan et al. 2017) which could explain the negative relationship between the two.

The positive correlation between zooplankton biomass and *C. finmarchicus* abundance confirmed the important contribution of this species to the total zooplankton biomass in the NW Atlantic. *C. finmarchicus* was also correlated with bloom initiation (-) and duration (+). Sub-adults 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 for that species associated to earlier and longer blooms, which in turns are favored by warmer climatic conditions (NL climate and winter NAO indices) and reduced sea ice cover.

5. Biogeochemical oceanographic highlights in 2020

- Spring bloom timing was near normal on the Labrador Shelf Flemish Cap, Southern Newfoundland, and Gulf of St. Lawrence; earlier than normal on the Newfoundland Shelf and the Georges Bank; and later than normal on the Grand Bank and the Scotian Shelf.
- Besides the unusually long bloom observed on the Georges Bank, bloom duration in 2020 was mostly near normal after two consecutive years of longer blooms in 2018-2019.
- Bloom magnitude (total production) was mostly near normal after two consecutive years of generally higher spring production.
- Mean nitrate inventories remained near normal for a second consecutive year after the below normal inventories recorded in 2018.
- Mean chlorophyll inventories remained near normal for a 4th consecutive year after six years of below normal levels and/or mostly negative anomalies.
- Both copepod and non-copepod mean abundance indices were above normal and among the highest of the time series.

- The abundance of *Calanus finmarchicus* copepods increased on the northern Newfoundland and Labrador shelves and the central and western Scotian Shelf , and decreased on the Flemish Cap, the Grand Bank, and the Bay of Fundy.

- The abundance of *Pseudocalanus* spp. copepods increased to above normal levels on the Newfoundland and Labrador shelves, but declined to near or below normal levels almost everywhere else in Canadian Shelf waters.

- Total zooplankton biomass increased to above normal levels on Newfoundland and Labrador shelves but declined in most of the Gulf of St. Lawrence and on the eastern Scotian Shelf.

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References

Blais M, Galbraith PS, Plourde S, Devine L and Lehoux C (2021) Chemical and biological oceanographic conditions in the Estuary and Gulf of St. Lawrence during 2019. DFO Can. Sci. Advis. Sec. Res. Doc. 2021/002. iv + 66 pp.

Bristow LA, Mohr W, Ahmerkamp S and Kuypers MM (2017) Nutrients that limit growth in the ocean. Curr 27: R431-R510

Casault B, Johnson C, Devred E, Head E, Cogswell A, and Spry, J. (2020). Optical, chemical, and biological oceanographic conditions on the Scotian Shelf and in the eastern Gulf of Maine in 2019. DFO Can. Sci. Advis. Sec. Res. Doc. 2020/071. v + 67 p.

Chiswell SM (2011) Annual cycles and spring blooms in phytoplankton: don't abandon Sverdrup completely. Mar Ecol Prog Ser 443:39-50

Colbourne E, Narayanan S and Prinsenberg S (1994) Climatic changes and environmental conditions in the Northwest Atlantic, 1970-1993. ICES J of Mar Sci Symp 198: 311-322

Cyr F, Snook S, Bishop C, Galbraith PS, Pye B, Chen N, Han G (2021) Physical oceanographic conditions on the Newfoundland and Labrador Shelf during 2019. DFO Can. Sci. Advis. Sec. Res. Doc. 2021/017 iv + 52 p.

Cyr F and Galbraith PS (2021) A climate index for the Newfoundland and Labrador Shelf. Earth Syst Sci Data 13: 1807-1828

Galbraith PS, Chassé J, Shaw J-L, Dumas J, Caverhill C, Lefaivre C, et Lafleur C (2020) Physical Oceanographic Conditions in the GSL during 2019. DFO Can. Sci. Advis. Sec. Res. Doc. 2020/030. iv + 84 p.

Head EJH and Pepin P (2008) Variations in overwintering depth distributions of *Calanus finmarchicus* in the slope waters of the NW Atlantic continental shelf and the Labrador Sea. J Northwest Atl Fish Sci 39: 49-69

Hebert D, Layton C, Brickman D, and Galbrait PS (2021) Physical oceanographic conditions on the Scotian Shelf and in the Gulf of Maine during 2019. DFO Can. Sci. Advis. Sec. Res. Doc. 2021/040. v + 58 p.

Holt J, Butenschön M, Wakeli SL, Artioli Y, Allen JI (2012) Oceanic controls on the primary production of the northwest European continental shelf: model experiments under recent past conditions and a potential future scenario. Biogeosciences 9:97-117

Jagadeesan L, Jyothibadu R Arunpandi N and Parthasarathi S (2017) Copepod grazing and their impact on phytoplankton standing stock and production in tropical coastal waters during different seasons. Environ Monit Assess 189: 105

Jónasdóttir SH, Gudfinnsson HG, Gislason A, Astthorsson OS (2002) Diet composition and quality for *Calanus finmarchicus* egg production and hatching success off south-west Iceland. Mar Biol 140: 1195-1206

Koen-Alonso M, Pepin P, Fogarty M, Kenny A, Kenchington E (2019) The Northwest Atlantic Fisheries Organization Roadmap for the development and implementation of an Ecosystem Approach to Fisheries: structure, state of development, and challenges. Mar Policy 100: 342-352

Maillet G, Bélanger D, Doyle G, Robar A, Fraser S, Higdon J, Ramsay D and Pepin P (2019) Chemical and biological oceanographic conditions on the Newfoundland and Labrador Shelf during 2016-2017. DFO Can. Sci. Advis. Sec. Res. Doc. 2019/055. Viii + 35 p.

Melle W, Runge F, Head E, Plurde S, and others (2014) The North Atlantic Ocean as habitat for *Calanus finmarchicus*: Environmental factors and life history traits. Prog Oceanogr 129: 244-284

Mitchell MR, Harrison G, Pauley K, Gagné A, Maillet G, Strain P (2002) Atlantic Zone Monitoring Program Sampling Protocol. Canadian Technical Report of Hydrography and Ocean Sciences 223, 23 pp.

Möllmann C, Kornilovs G, Fetter M, Köster FW (2004) Feeding ecology of central Baltic Sea herring and sprat. J Fish Biol 65:1563-1581

Murphy HM, Pepin P, and Robert D (2018) Re-visiting the drivers of capelin recruitement in Newfoundland since 1991. Fish Res 200: 1-10

Pendleton DE, Pershing AJ, Brown MW, Mayo CA, Kenedy, RD, Record NR, Cole TVN (2009) Regional-scale mean copepod concentration indicates relative abundance of North Atlantic right whales. Mar Ecol Prog Ser 378: 211-225

Pepin P, Colbourne E, Maillet G (2011) Seasonal patterns in zooplankton community structure on the Newfoundland and Labrador Shelf. Prog Oceanogr 91: 273-285

Plank B, Hays GC, Ibanez F, Gamble JC (1997) Large scale variations in the seasonal abundance of *Calanus finmarchicus*. Deep-Sea Res 44: 315-326

Plourde S, Lehoux C, Johnson CL and Lesage V (2019) North Atlantic right whale (*Eubalaena glacialis*) and its food: (I) a spatial climatology of *Calanus* biomass and potential foragind habitats in Canadian waters. J Plankton Res 41: 667-685

Rumyantseva A, Henson S, Martin A, Thompson AF, Damerell GM, Kaiser J, Heywood KJ (2019) Phytoplankton spring bloom initiation: The impact of atmospheric forcing and light in the temperate North Atlantic Ocean. Prog Oceanogr 178: 102202

Sigman DM and Hain MP (2012) The biological productivity of the ocean: section 4. Nature Educatio Knowledge 3(10): 21

Wilson CJ, Murphy H, Bourne C, Pepin P, Robert D (2018) Feeding ecology of autumn-spawned Atlantic herring (*Clupea harengus*) larvae in Trinity Bay, Newfoundland: Is recruitment linked to main prey availability? J Plank Res 00: 1-14

Yashayaev, I., Peterson I, E.J.H., Wang, Z. (2021). Meteorolical, sea ice, and physical oceanographic conditions in the Labrador Sea during 2018. DFO Can. Sci. Advis. Sec. Res. Doc. 2021/042. iv +26 p.

Zhai L, Platt T, Tang C, Sathyendranath S, Walls, RH (2011) Phytoplankton phenology on the Scotian Shelf. ICES J Mar Sci 68: 781-791

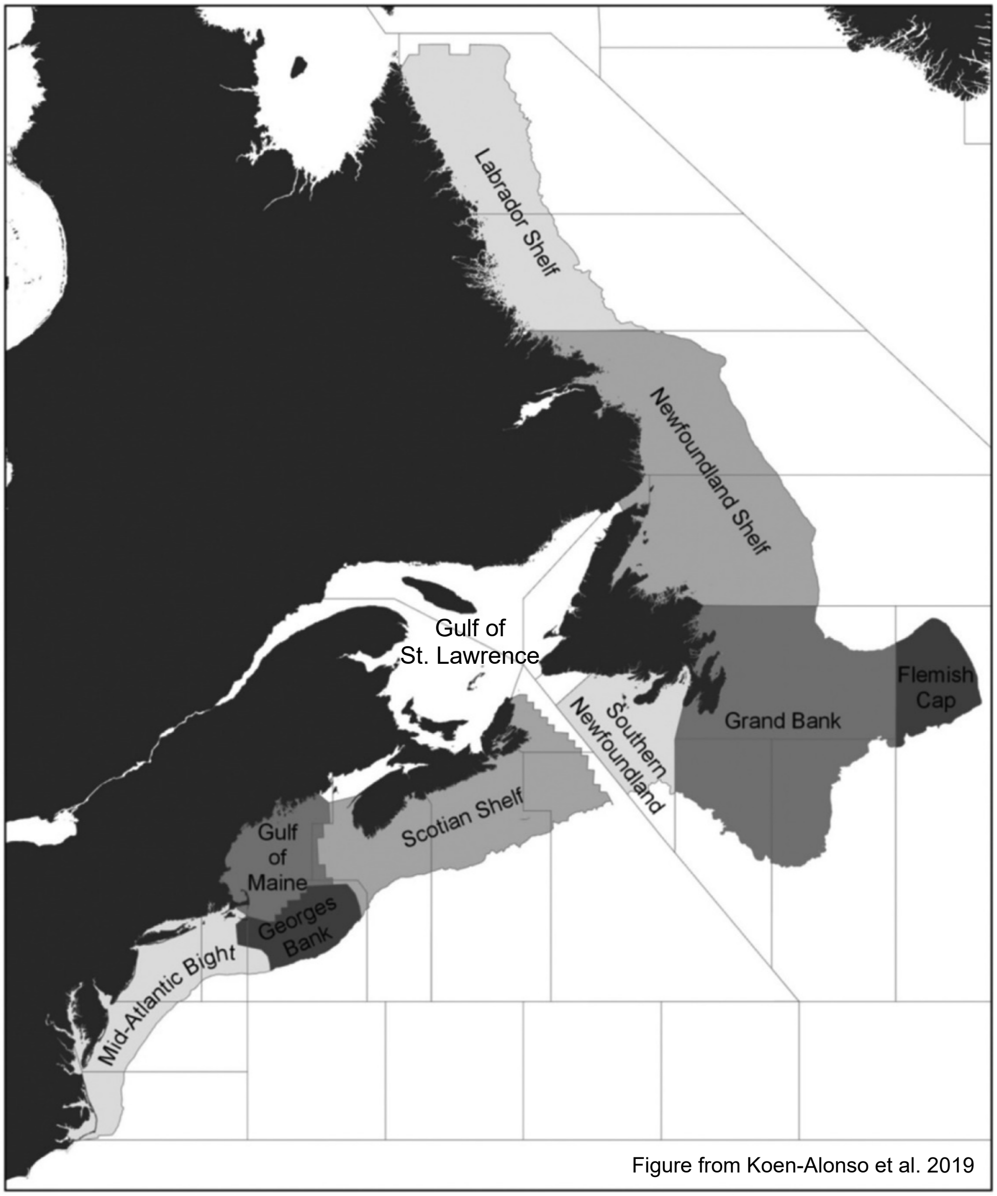

Figure 1. NAFO Ecological Production Units (EPUs) used to summarize biogeochemical oceanographic conditions and trends. The Gulf of St. Lawrence is also used as a grouping unit although it is not an official EPUs as defined by Koen-Alonso et al. 2019.

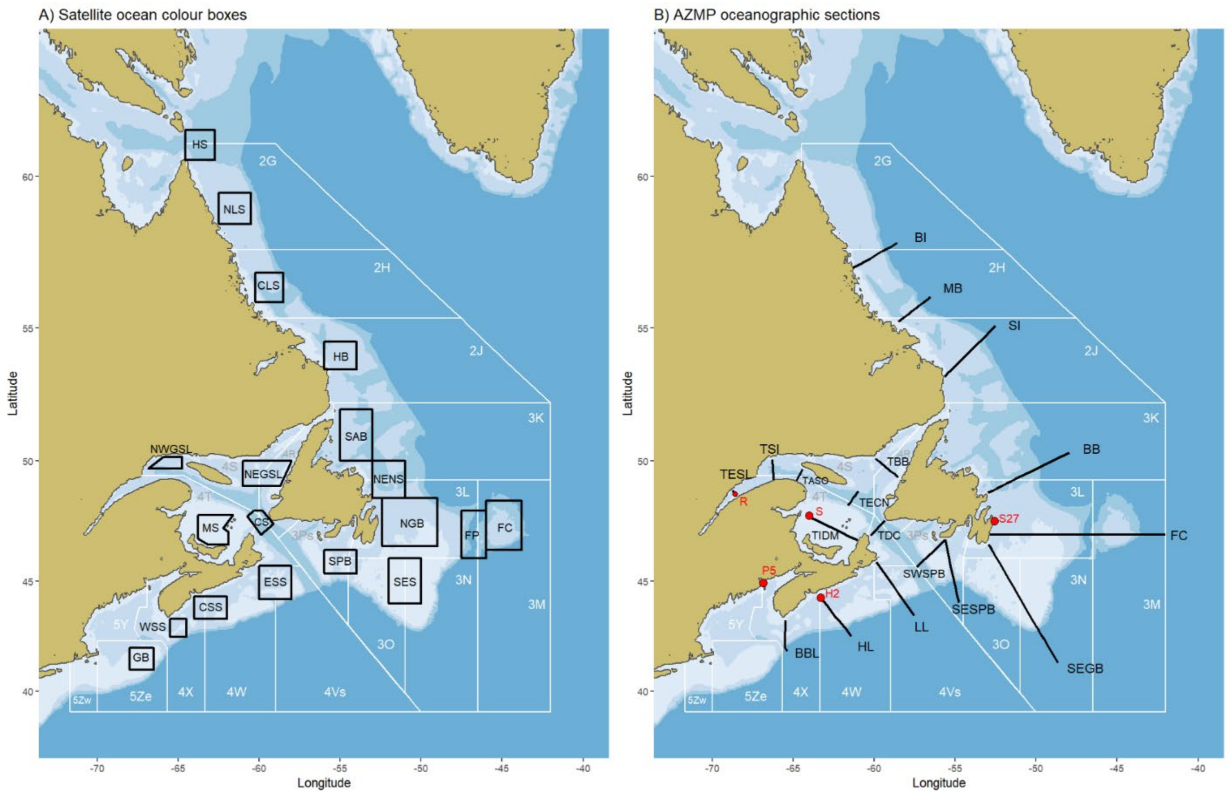

Figure 2. (A) Location of the boxes used to calculate spring bloom indices (initiation, duration, and magnitude) from satellite Ocean Color imagery: (HS=Hudson Strait, NLS=northern Labrador Shelf, CLS=central Labrador Shelf, HB=Hamilton Bank, SAB=St. Anthony Basin, NENS=northeast Newfoundland Shelf, 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 stations (red circles: S27=Station 27; R=Rimouski; S=Shediac Valley; H2=Halifax 2; P5=Prince 5) where chemical (nitrate) and biological (chlorophyll *a* and zooplankton abundance and biomass) data were collected.

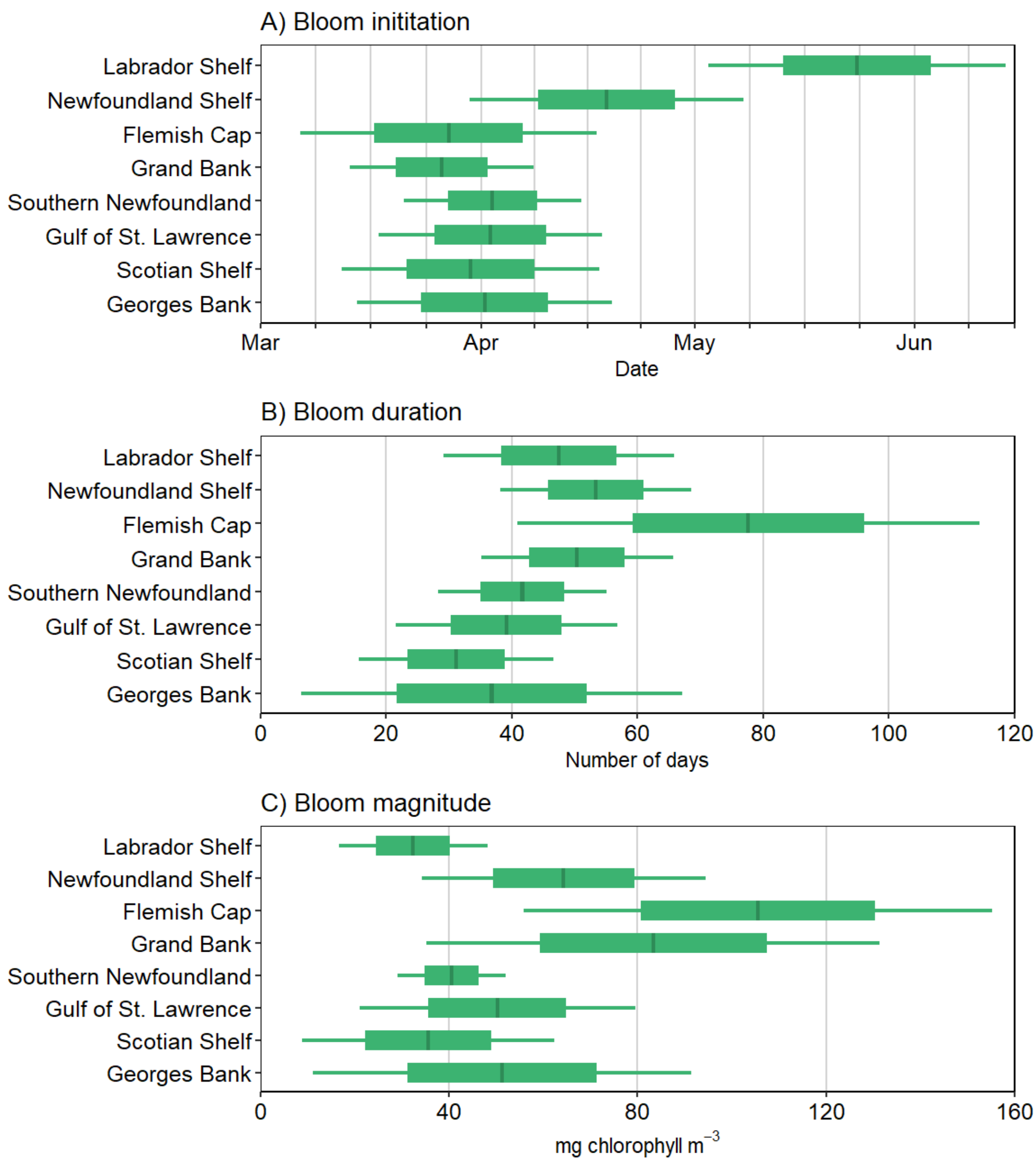

Figure 3. Mean values ± 0.5 SD (boxes) and ± 1 SD (whiskers) for the spring phytoplankton bloom (A) initiation, (B) duration, and (C) magnitude derived from ocean colour satellite data over the 2003-2020 reference period. The three parameters were calculated for seven NAFO Ecological Production Units (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.

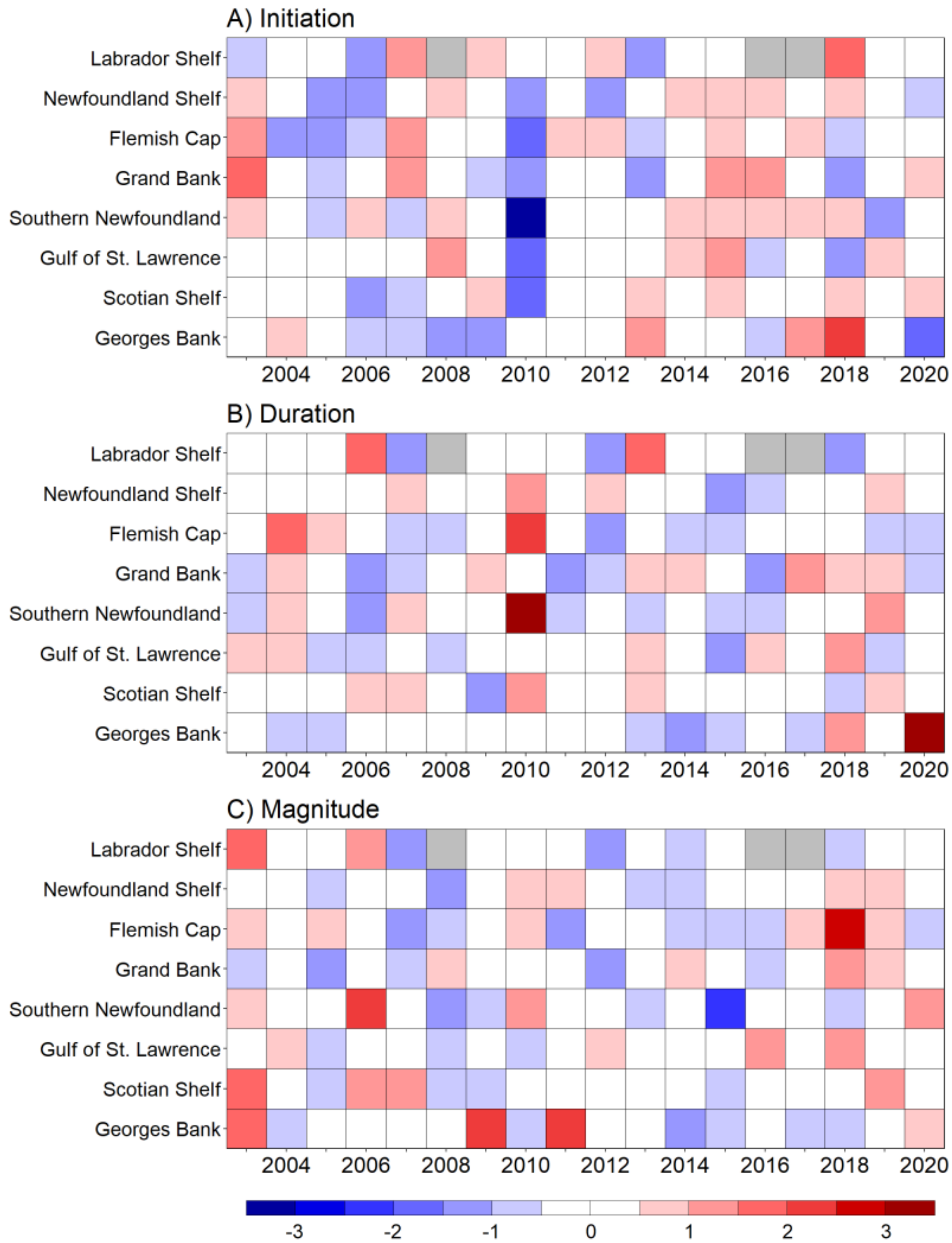

Figure 4. Annual standardized anomaly scorecards for the spring phytoplankton bloom (A) initiation, (B) duration, and (C) magnitude for seven NAFO Ecological Production Units (EPUs) and for the Gulf of St. Lawrence. Red (blue) cells indicate higher (lower) than normal conditions relative to the 2003-2020 reference period. White cells indicate near normal conditions, i.e. ± 0.5 SD. Grey cells indicate missing data. Regions are listed from North (top) to south (bottom). See Fig. 1 for EPUs locations.

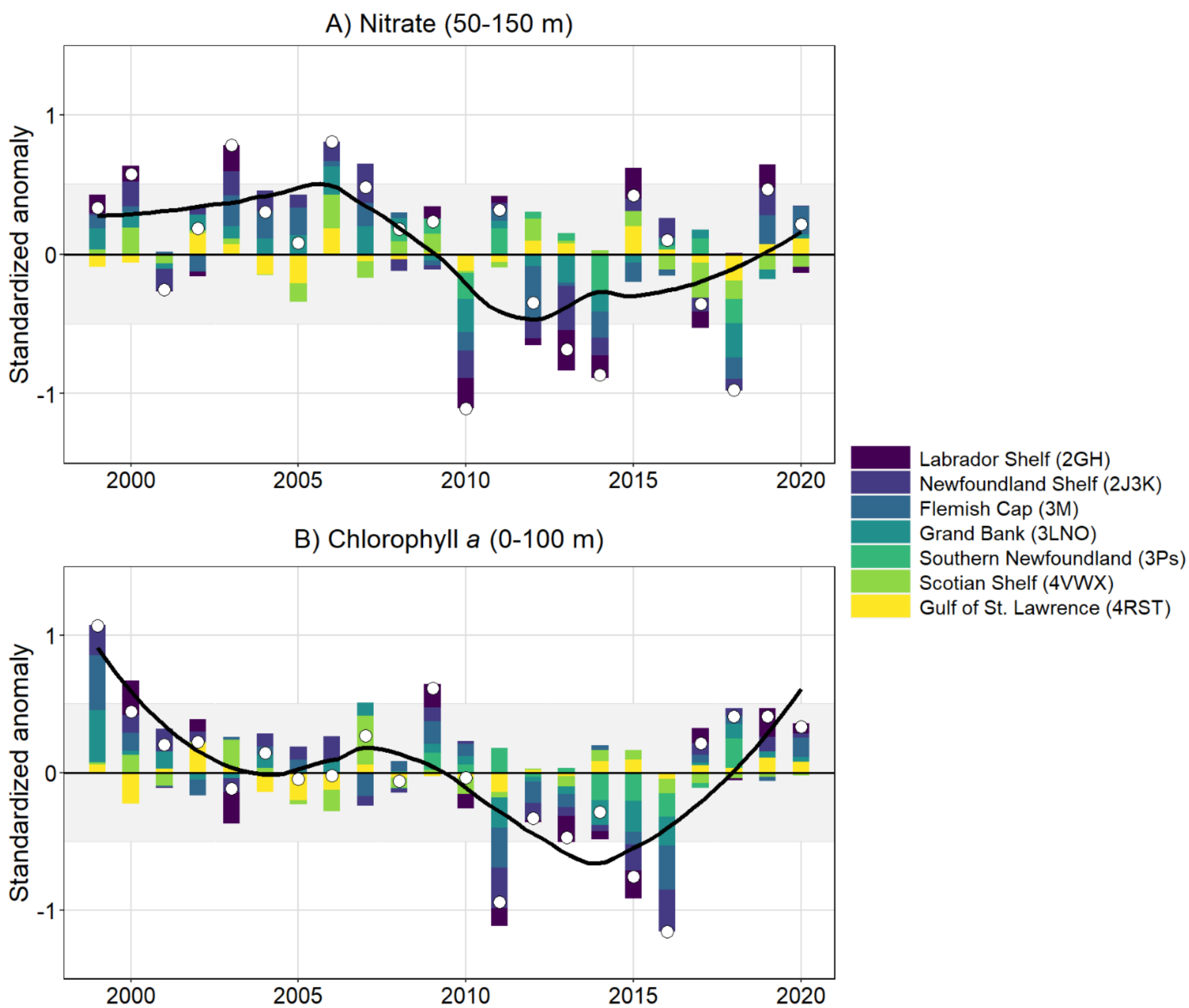

Figure 5. Annual anomaly time series of (A) 50-150 m integrated nitrate, and (B) 0-100 m integrated chlorophyll *a* inventories in NAFO Ecological Production Units (EPUs) and in the Gulf of St. Lawrence. Anomalies for each oceanographic sections and high-frequency monitoring stations were standardized based on a 1999-2020 reference period and averaged over NAFO Ecological Production Units (EPUs). White circle indicate the mean annual anomaly for the NW Atlantic. Colour bars indicate the relative weight of each EPU to the mean anomaly. The black line is a loess regression fitted to the annual mean anomalies and summarize the broad-scale temporal trend observed across NAFO EPUs and the Gulf of St. Lawrence. See Figs. 1 & 2B for the location of NAFO EPUs, and oceanographic sections and high-frequency monitoring stations, respectively.

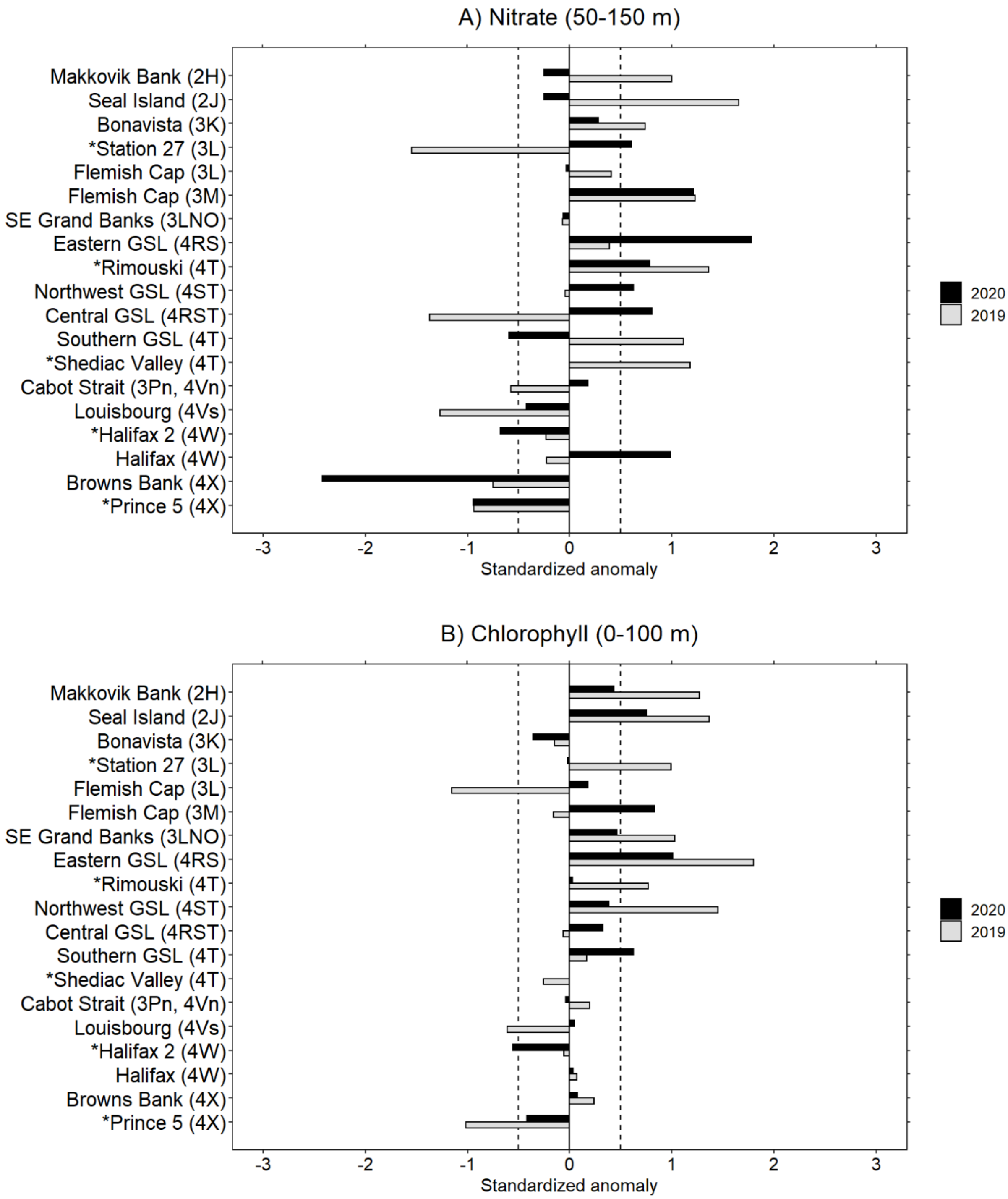

Figure 6. Comparison of seasonally corrected annual anomalies of (A) 50-150 integrated nitrate, and (B) 0-100 m integrated chlorophyll *a* inventories for each AZMP oceanographic sections and high-frequency monitoring stations in 2019 and 2020. Anomalies were calculated based on a 1999-2020 reference period. Anomalies within ±0.5 SD (vertical dashed lines) represent near-normal conditions. Sampling locations are listed from north (top) to south (bottom). Asterisks (*) indicate high-frequency monitoring stations. See Figure 2B for oceanographic sections and high-frequency monitoring station location.

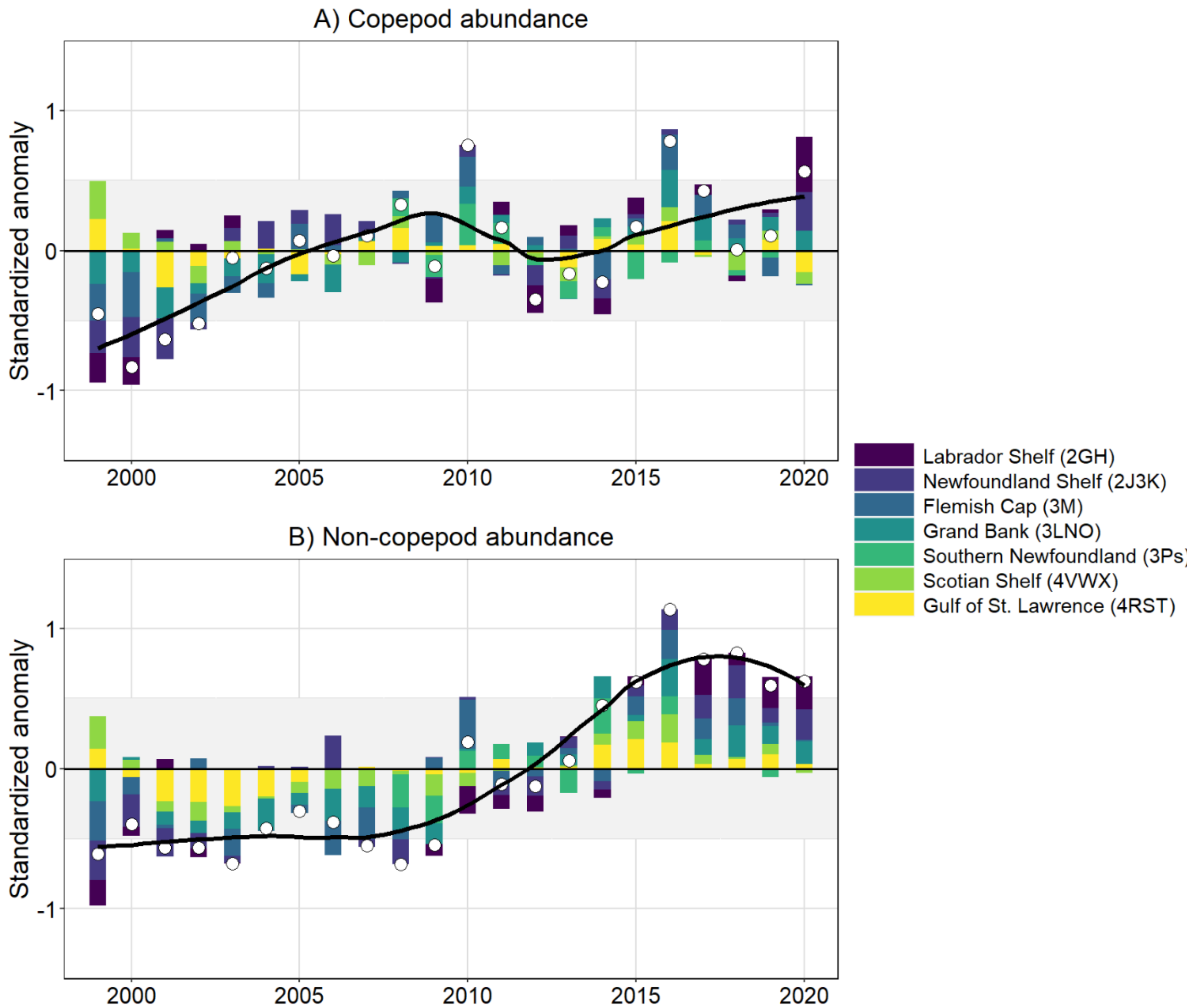

Figure 7. Anomaly time series of (A) copepod, and (B) non-copepod zooplankton abundance (ind. m^{-2}) in NAFO Ecological Production Units (EPUs) and in the Gulf of St. Lawrence. Anomalies for each oceanographic sections and high-frequency monitoring stations were standardized based on a 1999-2020 reference period and averaged over NAFO Ecological Production Units (EPUs). White circle indicate the mean annual anomaly for the NW Atlantic. Colour bars indicate the relative weight of each EPU to the mean anomaly. The black line is a loess regression fitted to the annual mean anomalies and summarize the broad-scale temporal trend observed across NAFO EPUs and the Gulf of St. Lawrence. See Figs. 1 & 2B for the location of NAFO EPUs, and oceanographic sections and high-frequency monitoring stations, respectively.

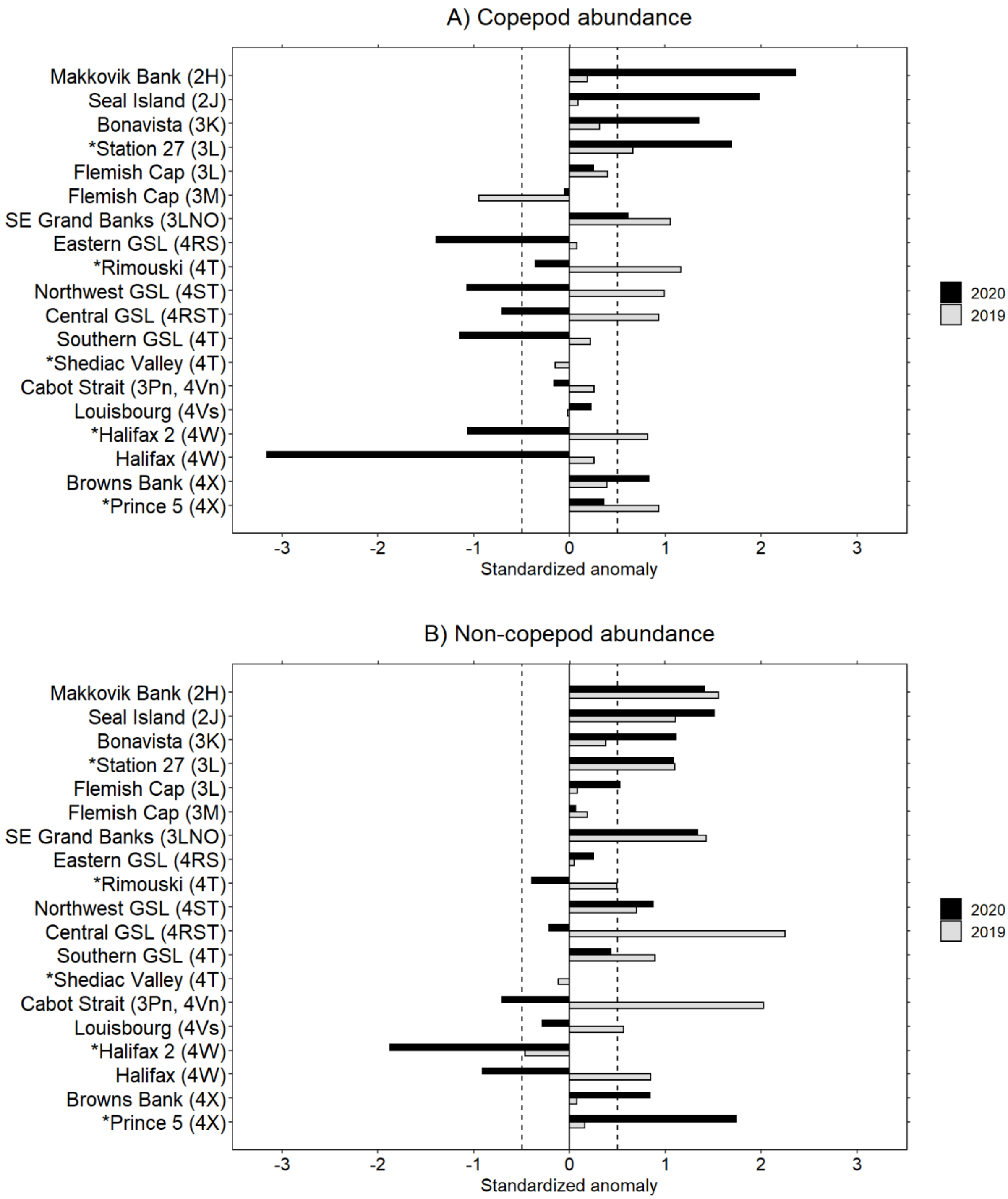

Figure 8. Comparison of seasonally corrected anomalies for copepod (A), and non-copepod (B) abundance (ind. m^{-2}) for each AZMP oceanographic sections and high-frequency monitoring stations in 2019 and 2020. Anomalies are calculated based on a 1999-2020 reference period. Anomalies within -0.5 and 0.5 (vertical dashed lines) are considered near normal conditions. Sampling locations are listed from north (top) to south (bottom). Asterisks (*) indicate high-frequency monitoring stations. See Figure 2B for oceanographic sections and high-frequency monitoring station location.

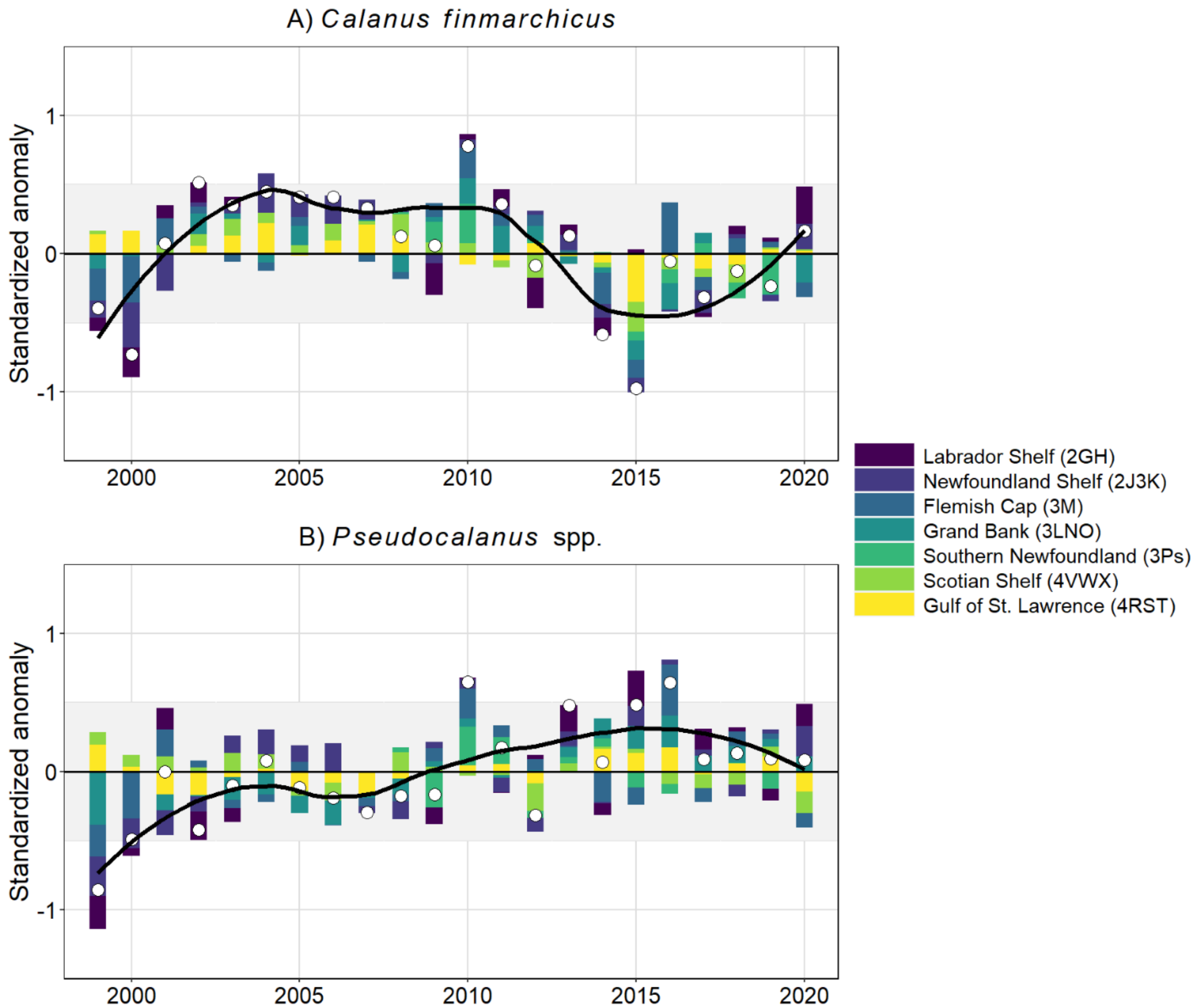

Figure 9. Annual anomaly time series of (A) *Calanus finmarchicus* and (B) *Pseudocalanus* spp. copepod abundance (ind. m^{-2}) in NAFO Ecological Production Units (EPUs) and in the Gulf of St. Lawrence. Anomalies for each oceanographic sections and high-frequency monitoring stations were standardized based on a 1999-2020 reference period and averaged over NAFO Ecological Production Units (EPUs). White circle indicate the mean annual anomaly for the NW Atlantic. Colour bars indicate the relative weight of each EPU to the mean anomaly. The black line is a loess regression fitted to the annual mean anomalies and summarize the broad-scale temporal trend observed across NAFO EPUs and the Gulf of St. Lawrence. See Figs. 1 & 2B for the location of NAFO EPUs, and oceanographic sections and high-frequency monitoring stations, respectively.

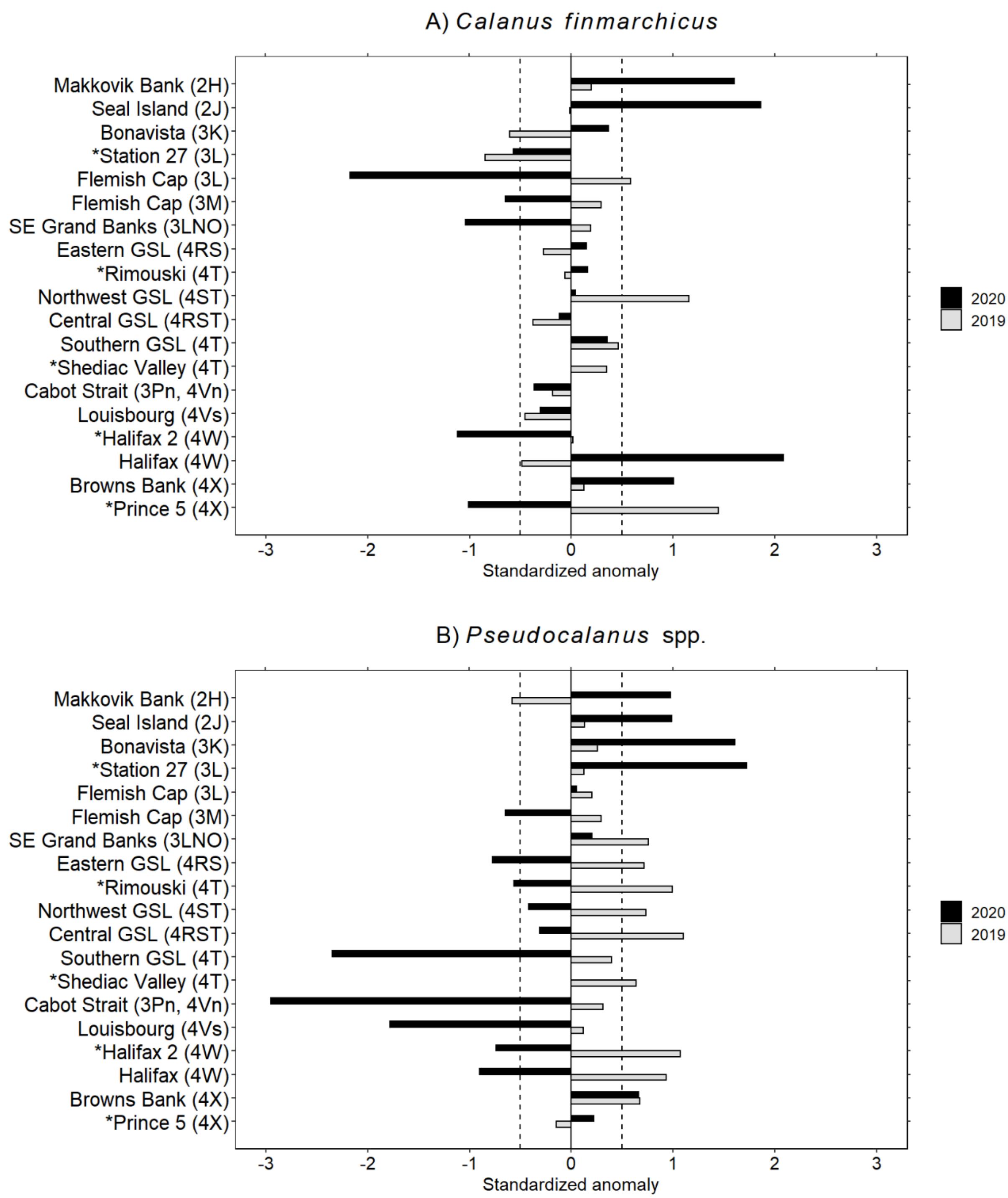

Figure 10. Comparison of seasonally corrected anomalies for (A) *Calanus finmarchicus*, and (B) *Pseudocalanus* spp. copepod abundance (ind. m^{-2}) for each AZMP oceanographic sections and high-frequency monitoring stations in 2019 and 2020. Anomalies were calculated based on a 1999-2020 reference period. Anomalies within -0.5 and 0.5 (vertical dashed lines) are considered near normal conditions. Sampling locations are listed from north (top) to south (bottom). Asterisks (*) indicate high-frequency monitoring stations. See Figure 2B for oceanographic sections and high-frequency monitoring station location.

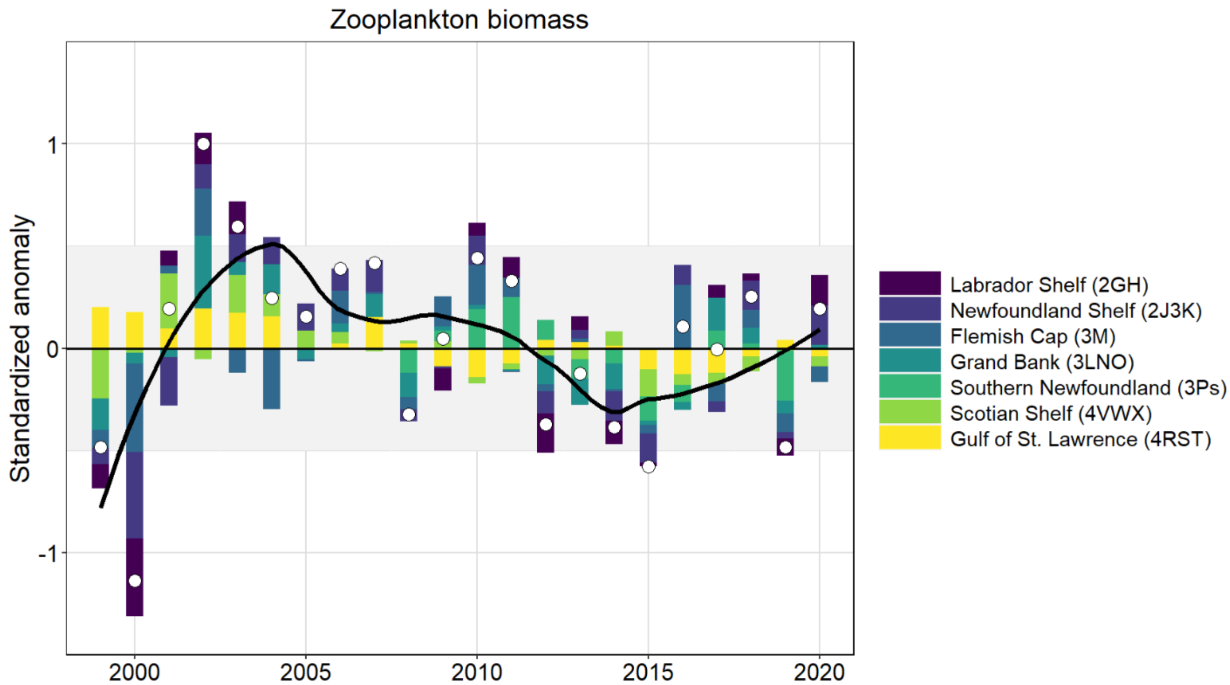

Figure 11. Annual anomaly time series of zooplankton biomass (g dry weight m^{-2}) in NAFO Ecological Production Units (EPUs) and in the Gulf of St. Lawrence. Anomalies for each oceanographic sections and high-frequency monitoring stations were standardized based on a 1999-2020 reference period and averaged over NAFO Ecological Production Units (EPUs). White circle indicate the mean annual anomaly for the NW Atlantic. Colour bars indicate the relative weight of each EPU to the mean anomaly. The black line is a loess regression fitted to the annual mean anomalies and summarize the broad-scale temporal trend observed across NAFO EPUs and the Gulf of St. Lawrence. See Figs. 1 & 2B for the location of NAFO EPUs, and oceanographic sections and high-frequency monitoring stations, respectively.

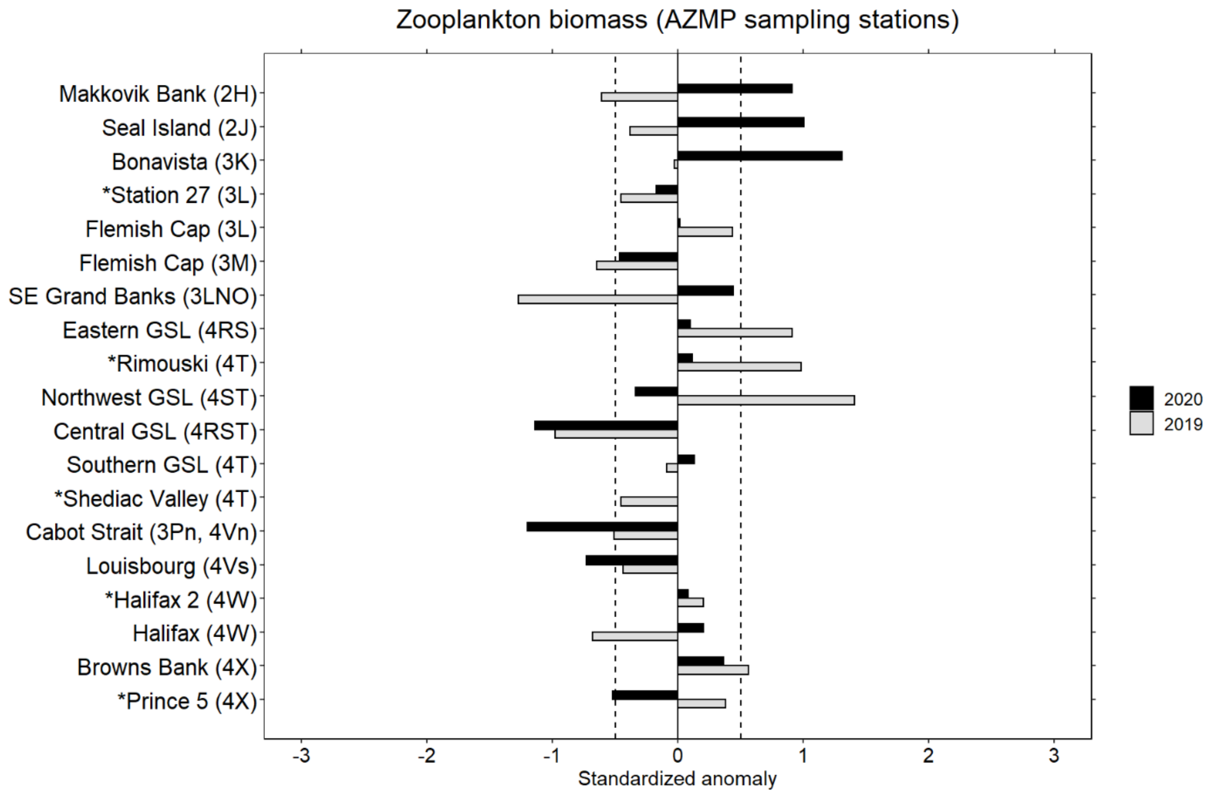

Figure 12. Comparison of seasonally corrected anomalies for zooplankton biomass (g dry weight m^{-2}) for each AZMP oceanographic sections and high-frequency monitoring stations in 2019 and 2020. Anomalies are calculated based on a 1999-2020 reference period. Anomalies within -0.5 and 0.5 (vertical dashed lines) are considered near normal conditions. Sampling locations are listed from north (top) to south (bottom). Asterisks (*) indicate high-frequency monitoring stations. See Figure 2B for oceanographic sections and high-frequency monitoring station location.

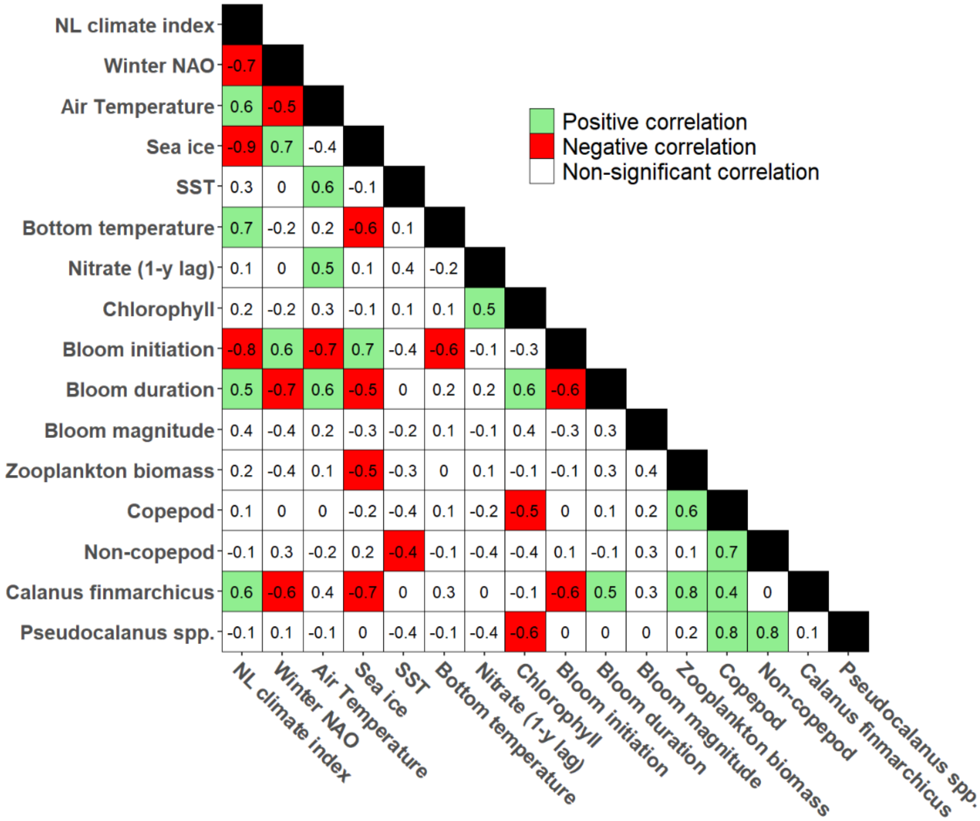

Figure 13. Correlation matrix summarizing the relationships between physical (Newfoundland and Labrador climate index, winter North Atlantic Oscillation [NAO] index, air temperature, sea ice cover, sea surface temperature [SST], and bottom temperature), and biogeochemical (phytoplankton spring bloom 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 1999-2020 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.