Northwest Atlantic Fisheries Organization

Serial No. N7083 **NAFO SCR Doc. 20/035**

SCIENTIFIC COUNCIL MEETING – JUNE 2020

Biogeochemical oceanographic conditions in the Northwest Atlantic (NAFO subareas 2-3-4) during 2019

by

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Abstract

Biogeochemical variables collected in 2019 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 interannual variations in phytoplankton spring bloom indices as well as nitrate (50-150 m), chlorophyll *a* (0-100 m), zooplankton abundance, and zooplankton biomass inventories collected during the 2019 Atlantic Zone Monitoring Program (AZMP). Spring bloom timing and duration were near normal in all regions except on the Newfoundland Shelf and the Grand Bank (GB) where earlier and longer-than-normal blooms were observed. Bloom magnitude was below normal in all regions, especially in the Gulf of St. Lawrence (GSL) where spring production reached a record low after several consecutive years of above-normal production. In general, nitrate inventories increased on the Newfoundland and Labrador (NL) shelves and the FC in 2019 compared to the previous year, but remained low on the GB and the Scotian Shelf (SS). Chlorophyll inventories were mostly above normal on the NL shelves, the GB, and the GSL, and near to below normal on the SS. The abundance of copepod and non-copepod zooplankton were near to above normal in all regions although no data were available for the Labrador Shelf, the GB, and the Southern Newfoundland for this report. Copepod abundance increased from below-normal to near or above-normal levels on the SS in 2019 compared to 2018. The abundance of large *Calanus finmarchicus* copepods was mainly near normal in 2019 which represented an increase compared to the previous year. The abundance of small *Pseudocalanus* spp. copepods was near to above normal in all regions in 2019, continuing an increasing trend observed since 1999. Zooplankton biomass was near to below normal in most regions. The low biomass on the NL shelves and the GB in 2019 contrasted with above-normal levels observed in 2018. However, biomass indices for these regions were calculated on partial datasets and the general pattern for 2019 may change when all data become available.

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1. Introduction

Here, we review the biogeochemical oceanographic conditions in Northwest Atlantic shelf waters within NAFO Subareas 2, 3 and 4. We present results collected in 2019, and reference earlier periods where data are available. Directed seasonal sampling on oceanographic sections by the Atlantic Zone Monitoring Program (AZMP[1]) and at coastal high-frequency monitoring stations by ships of opportunity provided reasonable spatial and temporal series coverage. Annual collection of standard variables (temperature, salinity, nutrients, chlorophyll, zooplankton abundance, biomass and composition) since 1998/1999 allows to compare patterns of variation and trends among ecologically relevant chemical and biological indices in the Northwest (NW) Atlantic. We use NAFO Ecological Production Units (EPUs) and the Gulf of St. Lawrence as grouping factors to summarise biogeochemical oceanographic conditions and trends at a scale deemed to be best suited for integrated ecosystem management plans in the Northwest Atlantic (Koen-Alonso et al. 2019; see Figure 1 for EPUs location). Additional details on physical, chemical and biological oceanographic conditions in the NW Atlantic in 2018 and earlier years can be found in Blais et al. (2019), Cyr et al. (2020), Galbraith et al. (2019), Hebert et al. (2018), Johnson et al. (2018), Maillet et al. (2019), Yashayaev et al. (2014).

2. Methods

Surface phytoplankton biomass was estimated from ocean colour satellite data collected by the Sea-viewing Wide Field-of-view Sensor (SeaWiFS; (https://oceancolor.gsfc.nasa.gov/SeaWiFS/), Moderate Resolution Imaging Spectroradiometer (MODIS) "Aqua" sensor (http://modis.gsfc.nasa.gov/), and the Visible-Infrared Imager Radiometer Suite (VIIRS) sensor (https://oceancolor.gsfc.nasa.gov/data/viirs-snpp/). The SeaWiFS time series began in September of 1997, MODIS data stream began in July 2002, and VIIRS availability is January 2012 to present. Satellite data do not provide information on the vertical structure of chlorophyll (chl *a*) pigments in the water column but do provide large scale, highly resolved (~1.5 km) data on their geographical distribution in surface waters. Eight-day composite images of chl *a* surface concentrations for the entire NW Atlantic (39-62.5° N Latitude 42-71° W Longitude) were routinely produced from SeaWiFS/MODIS/VIIRS data[2]. Basic statistics (mean, range, standard deviation, etc.) were extracted from the composites for selected subregions (Figure 2A) and used to calculate phytoplankton spring bloom indices. Time series of bloom initiation, duration , and magnitude from 1998 to 2019 were constructed by applying the calculation method developed by Zhai et al. (2011) to available satellite data from the SeaWiFS (1998-2007), MODIS (2008-2011), and VIIRS (2012-2018) sensors.

Collections of standard AZMP variables are based on sampling protocols outlined by Mitchell *et al*. (2002). Observations for 2019 and earlier years presented in this document are based on seasonal surveys conducted during spring, summer and fall (typically March through December). The coastal high-frequency monitoring stations are typically sampled at twice monthly to monthly intervals during ice-free conditions. The location of the standard oceanographic sections and high-frequency monitoring stations are shown in Figure 2B. Standardized anomalies were used to summarize 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

[1] http://www.meds-sdmm.dfo-mpo.gc.ca/isdm-gdsi/azmp-pmza/index-eng.html
[2] http://www.bio.gc.ca/science/newtech-technouvelles/sensing-teledetection/index-en.php

by subtracting the mean of the long-term reference period (RP: 1998-2015 for satellite ocean colour data, and 1999-2015 for AZMP survey data) 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 Ocean colour satellite data (spring bloom magnitude, initiation, and duration) were calculated on non-transformed data. Annual standardized anomalies for integrated nitrate (50-150 m) and chlorophyll (0-100 m) inventories; copepod, non-copepod, *Calanus finmarchicus*, and *Pseudocalanus* spp, abundance; and zooplankton biomass were calculated from least square means of linear models with the fixed factors Year, Season and Station (standard oceanographic sections) or Year and Season (coastal high-frequency monitoring stations) applied 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. Values within ± 0.5 SD from the climatological mean indicate near normal conditions. Positive values > 0.5 SD indicate conditions above the climatological mean. Negative values < 0.5 SD indicate conditions below the climatological mean. Annual standardizes anomalies were calculated for each oceanographic sections and high-frequency monitoring stations and averaged over NAO EPUs (Labrador Shelf, Newfoundland Shelf, Flemish Cap, Grand Bank, Southern Newfoundland, Scotian Shelf, and Georges Bank) and the Gulf of St. Lawrence. The standard 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* (mmol 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 large-scale spatial trends in the chemical and biological in situ observations across the NW Atlantic, a cumulated anomaly index was calculated for each sampling year by summing the annual anomalies of each AZMP oceanographic sections and high-frequency monitoring stations.

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

3.1. Phytoplankton Spring Bloom

The initiation of the phytoplankton spring bloom along the eastern Canadian Shelf occurs earlier in the south compared to regions to the north (Figure 3A). Spring bloom typically starts in late March to early April on the Georges Bank, during the las two weeks of March on the Scotian Shelf, and during the first two weeks of April in the Gulf of St. Lawrence and Southern Newfoundland (Figure 3A). The bloom starts between the last week of March and the first week of April on the Grand Bank, around mid-April on the Flemish Cap and the Newfoundland Shelf, and during the third week of May on the Labrador Shelf (Figure 3A). Extensive sea ice cover on the Labrador Shelf in the spring delays the initiation of the bloom is this region.

Phytoplankton spring bloom initiation (Figure 4A) did not show clear spatial or temporal trends throughout the 22 years time series. Early blooms (negative anomalies) observed across most of the eastern Canadian Shelf in 1999 were followed by a period of mostly near-normal or late (positive anomalies) timing across the region between 2001 and 2004. Early blooms occurred on the Grand Bank to the north in 2005 and 2006, but timing returned to normal in 2007. Notably early blooms occurred in the Southern Newfoundland and the Gulf of St. Lawrence in 2010. There was seven consecutive years of normal to late blooms on the Grand Bank and Southern Newfoundland between 2011 and 2017, while bloom initiation oscillated between late and early in the Gulf of St. Lawrence and on the Scotian Shelf during the same period. In 2019, bloom initiation was near normal in most regions except on the Newfoundland Shelf and the Grand Bank where blooms occurred slightly earlier than normal (Figures 3A, 4A). Limited satellite coverage caused by extensive cloud cover over the OC boxes on the Labrador Shelf (see figure 2A for box locations) prevented the calculation of spring bloom indices (initiation, duration and magnitude) for that region.

The duration of the spring bloom increases with latitude on the eastern Canadian Shelf. Blooms typically last ~30 days on the Georges Bank, the Scotian Shelf, and in Southern Newfoundland, 35 days in the Gulf of St. Lawrence and on the Grand Bank and the Newfoundland Shelf, 45 days on the Flemish Cap, and 50 days on the Labrador Shelf (Figure 3B). The duration f the bloom varied more on the Labrador Shelf and the Flemish Cap compared to other regions (Figure 3B). The lower satellite coverage due to sea ice and clouds over the Ocean Color boxes along the Labrador shelf may increase the uncertainty around bloom duration (see figure

2A for box locations). Bloom duration was mainly near to above normal from the beginning of the time series until the mid-2000s, and decreased to near or below normal through the mid-2010s with the exception of few longer than normal blooms including a record high duration in Southern Newfoundland in 2010 (Figure 4B). Bloom duration then increased again since the mid 2010s, especially in the Gulf of St. Lawrence and on the Scotian Shelf and the Georges Bank (Figure 4B). Bloom duration was mostly near normal in 2019 for a second consecutive year with the exception of the longer blooms observed on the Grand Bank and the Newfoundland Shelf (Figures 3B, 4B).

The magnitude, i.e. the total production, of the spring bloom showed an overall decrease since the beginning of the monitoring program in 1998. Although no consistent temporal trends could be observed between 1998 and 2006, the positive anomalies frequently observed across the regions during that period gave place to mainly near normal conditions through 2014, and to below-normal spring production from the mid-2010s onwards (Figure 4C). The Gulf of St. Lawrence, where above-normal production has been observed in most years since 2012, including a record high spring production in 2017, is an exception (Figure 4C). Bloom magnitude in 2019 was below normal in all regions including a record-low production in the Gulf of St. Lawrence (Figure 4C).

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 (Figure 5A). The cumulated anomaly index was positive in 2019 for the second time only since 2010. Mean nitrate anomalies were positive for the Flemish Cap and the Newfoundland and Labrador shelves, negative for Grand Bank and the Scotian Shelf, and near zero for the Gulf of St. Lawrence (Figure 5A). The Southern Newfoundland index was not available for 2019. Nitrate inventories increased from below normal in 2018 to above normal in 2019 on most AZMP oceanographic sections and high-frequency monitoring stations on the Newfoundland and Labrador shelves (2GHJ3K) and in the Gulf of St. Lawrence (4RST), but remained near or below normal on the Grand Bank (3LMNO) and the Scotian Shelf (4VWX) (Figures 6A).

The overall, large-scale temporal trend in integrated (0-100 m) chlorophyll *a* inventories was similar to that of nitrate with mostly positive cumulated anomaly indices throughout the 2000s, followed by negative cumulated indices from 2010 to 2016 (Figure 5B). However, contrary to nitrate, chlorophyll concentration has increased in recent years after reaching a time series record low in 2016. Cumulated indices have remained positive since 2017 although lower chlorophyll inventories persisted on the Scotian Shelf during that period (Figure 5B). The general spatial pattern of variation in chlorophyll concentration along AZMP oceanographic sections was similar for 2018 and 2019 with mostly near to above-normal levels on the Newfoundland and Labrador shelves (2GHJ3K), the Grand Bank (3LNO), and in the Gulf of St. Lawrence (4RST), and near to below-normal levels on the Scotian Shelf (4VWX) (Figure 6B). The decline in chlorophyll concentration from above to below-normal levels along the Flemish Cap section (3LM) in 2019 was the main exception to the overall continuity in chlorophyll trend (Figure 6B).

3.3 Zooplankton Abundance

The abundance (ind. m^{-2}) of copepods showed an overall increasing trend across all regions since the beginning of the AZMP in 1999 (Figure 7A). Copepod abundance increased consistently during most of the 2000s, leveled off during the late 2000s and early 2010s, before increasing again until 2019. The cumulated index for 2019 was not calculated because data for the for the Labrador Shelf, the Flemish Cap, and Southern Newfoundland were not available for this report. However, copepod abundance anomalies were positive in all presented regions, i.e. the Newfoundland Shelf, the Grand Bank, the Scotian Shelf, and the Gulf of St. Lawrence (Figure 7A). The comparison between 2018 and 2019 indices showed that copepod abundance remained near normal along the Seal Island (2J), and western (4ST) and southern (4T) Gulf of St. Lawrence AZMP sections and at the Shediac Valley (4T) high-frequency monitoring station, and above normal at Station 27 (3L) and Rimouski (4T) stations (Figure 8A). Copepod abundance increased from below to above-normal levels along the eastern Gulf of St. Lawrence sections (4RS) and at the Prince 5 station in the Bay of Fundy (4X), and from near normal to above-normal levels at the Halifax 2 station (4W) (Figure 8A).

The abundance on non-copepod zooplankton remained stable throughout the 2000s, and drastically increased during the 2010s (Figure 7B). The cumulated index has constantly increased since 2011 and anomalies have remained positive across all regions since 2016. As for copepods, the cumulated index was not calculated for 2019 due to the non-availability of data for the Labrador Shelf, Flemish Cap, and Southern Newfoundland regions. Spatial anomaly pattern for non-copepod zooplankton in 2019 was similar to that observed in 2018 with near to above-normal levels across nearly all AZMP oceanographic sections and high-frequency monitoring stations (Fig 8B). The increase in non-copepod abundance was higher on the Newfoundland and Labrador shelves (2GHJ3K) and the Grand Bank (3LMNO) than in the Gulf of St. Lawrence (4RST) and on the Scotian Shelf (4VWX) (Figure 8B). However, large increase were observed in 2019 along the western Gulf of St. Lawrence (4ST) and Cabot Strait (3Pn4Vn) sections (Figure 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). Large-scale trend showed that the abundance of *C. finmarchicus* increased in the early 2000s, leveled off during the mid- and late 2000s, and decrease throughout the 2010s (Figure 9A). Non-availability of data for the Labrador Shelf, Flemish Cap and Southern Newfoundland in 2019 prevented the calculation of the cumulated anomaly index for that year. Anomaly pattern for *C. finmarchicus* abundance in 2019 was similar to that observed in 2018 with near to below-normal levels along most AZMP sections and high-frequency monitoring stations (Figure 10A). However, *C. finmarchicus* abundance markedly decreased at Station 27 (3L), increased from below-normal to near-normal levels along the eastern Gulf of St. Lawrence (4RS) and Brown Bank (4X) sections, and from below-normal to above-normal levels at the high-frequency monitoring station Prince 5 in the Bay of Fundy (Figure 10A).

Pseudocalanus spp. are highly abundant, widely distributed 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, Wilson et al. 2018). Large-scale trend in the abundance of *Pseucalanus* spp. copepods indicate a constant increase throughout the 21-year time series (Figure 9B). However, the increased *Pseudocalanus* spp. abundance has leveled off since the mid-2010s with negative anomalies observed in four consecutive years between 2015 and 2018 on the Scotian Shelf (Figure 9B). Spatial patterns in *Pseudocalanus* spp. abundance were similar for 2018 and 2019 with mainly near to above-normal levels on the Newfoundland and Labrador shelves (2GHJ3K), the Grand Bank (3LNO), and in the Gulf of St. Lawrence (4RST), and negative anomalies on the Scotian Shelf (4VWX) (Figure 10B). However, *Pseudocalanus* spp. abundance increased from below-normal to near normal levels in most sections on the Scotian Shelf, and from below-normal to above-normal levels at the Prince 5 (4X) station in the Bay of Fundy (Figure 10B).

3.4. Zooplankton biomass

Archiving errors in the DFO NL zooplankton database were discovered in 2019. Wrongly corrected biomass led to an underestimation of the zooplankton biomass for the 2015-2018 period. Also, the addition to the database of omitted biomass samples for the period 2013-2015 affected the climatological means for the 1999-2015 reference period and, therefore, the biomass anomalies reported in previous NAFO SCR reports by and Bélanger et al. 2018 and 2019 (see Appendix 1 and Figure A1 for more details). We wish to highlight that this issue only concerns zooplankton biomass and did not affect previously reported zooplankton abundance indices.

Large-scale trend showed an increase in zooplankton biomass during the early 2000s followed by a constant decrease from 2004 through 2014 (Figure 11). Zooplankton biomass started to recover on the Newfoundland and Labrador shelves, the Flemish Cap and the Grand Bank in the mid-2010s, but remained low on the Scotian Shelf and in the Gulf of St. Lawrence (Figure 11). Again, zooplankton cumulated index was not calculated in 2019 due to data unavailability for the Labrador Shelf, Flemish Cap, and Southern Newfoundland regions. Comparison of zooplankton biomass comparison between 2018 and 2019 showed similar trends of near to below-normal levels on Scotian Shelf (4VWX), but contrasting results for most of the Newfoundland shelf, Grand Bank, and Gulf of St. Lawrence regions (Figure 12). Biomass decreased from above-normal to near and below-normal along the Seal Island (2J) section and at Station 27 (3L), respectively, contrasting with the increase from below-normal to above-normal levels along the western Gulf of St. Lawrence sections and at the Rimouski station (Figure 12).

4. Large-scale relationships between climatic and biogeochemical indices

Pearson correlations applied to cumulated physical and biogeochemical indices were used to investigate relationships among climatic (North Atlantic Oscillation [NAO], air temperature, sea ice cover, sea surface temperature [SST], cold intermediate layer [CIL] volume, and sea bottom temperature) and biogeochemical (phytoplankton spring bloom initiation, duration and magnitude; 50-150 m integrated nitrate inventories; 0-100 m integrated chlorophyll *a* inventories; abundance of copepod, non-copepod, *Calanus finmarchicus*, and *Pseudocalanus* spp.; zooplankton biomass) indices across NAFO subareas 2, 3, and 4 (Figure 13). Negative correlations between spring bloom initiation air temperature ($r = -0.76$, $p < 0.01$), SST ($r = -0.51$, $p = 0.02$), and bottom temperature ($r = -0.53$, $p = 0.01$) highlights the role of environmental conditions in controlling the timing of the bloom in temperate seas. Higher air temperature in spring favor early onset of thermal stratification of surface waters which is critical to phytoplankton buildups (Chiswell 2011, Rumyantseva et al. 2019). Interestingly, there was no significant correlation between nitrate inventories and primary production indices despite the major limiting effect of nitrate on ocean primary production (Holt et al. 2012). Nonetheless, the direction of the correlations between nitrate inventories and bloom and magnitude as well as with integrated chlorophyll inventories were positive as expected.

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 incidentally impact the state of several ecologically and economically important stocks ranging 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 copepod and non-copepod zooplankton were positively correlated ($r = 0.56$, $p= 0.01$) which suggest large-scale community response to changing environmental conditions in the NW Atlantic. The positive and negative correlations between the abundance of non-copepod zooplankton and NAO ($r = 0.49$, $p = 0.03$), and SST ($r = -0.53$, $p = 0.02$) indices, respectively, suggest that the large increase in non-copepod abundance observed since the mid-2010s is associated with the cooler climatic conditions during that period. (positive NAO phase = cooler climatic conditions in the Northwest Atlantic, and vice versa; Cyr et al. 2020). Conversely, the negative correlations between the abundance of *C. finmarchicus* and NAO ($r = -68$, $p < 0.01$) and see ice cover ($r= = -0.46$, $p = 0.04$) along with the positive correlations with air temperature ($r = 0.5$, $p = 0.02$) and SST ($r = 0.59$, $p = 0.01$) suggest that low *C. finmarchicus* abundance may be associated cooler climatic conditions.

The strong positive correlation between zooplankton biomass and *C. finmarchicus* abundance ($r = 0.79$, $p < 0.01$) confirmed the important contribution of this species to the total zooplankton biomass in the Northwest Atlantic. Both zooplankton biomass ($r = 0.66$, $p < 0.01$) and *C. finmarchicus* abundance ($r = 0.61$, $p < 0.01$) were positively correlated to spring bloom magnitude. Studies showed that egg production in *C. finmarchicus* copepods is positively correlated with phytoplankton biomass in the North Atlantic (Jónasdóttir et al 2002). *C. finmarchicus* recruitment in the Northwest Atlantic may have been affected the overall decline in spring bloom production that started in the late 2000s leading to a decline in zooplankton biomass (see Figures 4C, 9A and 11). The positive correlation between copepod abundance and *Pseudocalanus* spp. ($r = 0.64$, $p < 0.01$) highlights the importance of the latter as an indicator of the general trends in total copepod abundance. Significant correlations observed between NAO and zooplankton biomass ($r = -0.47$, $p = 0.03$), *C. finmarchicus* abundance, and non-copepod abundance indicate that large-scale variations in climatic conditions are important driving forces controlling the zooplankton community structure and composition in the Northwest Atlantic.

5. Biogeochemical oceanographic highlights in 2019

- Spring bloom initiation was near normal in most regions except on the Newfoundland Shelf and the Grand Bank where blooms occurred slightly earlier than normal.

- Bloom duration was near normal for a second consecutive year with the exception of the longer blooms observed on the Grand Bank and the Newfoundland Shelf.

- Bloom magnitude (i.e. total production) was below normal in all regions including a record-low spring production in the Gulf of St. Lawrence.

- Integrated (50-150 m) nitrate inventories were mostly above normal on the Newfoundland and Labrador shelves and in the Gulf of St. Lawrence, but near or below normal on the Grand Bank and the Scotian Shelf .

- Integrated (0-100 m) chlorophyll inventories were mostly near to above-normal levels on the Newfoundland and Labrador shelves, the Grand Bank, and in the Gulf of St. Lawrence, near to below-normal levels on the Scotian Shelf, and below-normal on Flemish Cap.

- Copepod abundance remained above normal at Station 27 (3L), in the eastern Gulf of St. Lawrence for a second consecutive year, and generally increased on the Scotian Shelf.

- Non-copepod abundance was above normal in most regions across the eastern Canadian Shelf.

- The abundance of *Calanus finmarchicus* copepods was mostly near normal across the eastern Canadian Shelf with the exception of the strong positive and negative anomalies observed at the Prince 5 (Bay of Fundy, 4X)) and Station 27 (3L) high-frequency monitoring stations.

- The abundance of *Pseudocalanus* spp. copepods was above normal in Gulf of St. Lawrence and in the Bay of Fundy (4X), and near normal on the NL shelves, the Grand Bank, and the Scotian Shelf.

- Total zooplankton biomass was mainly near to below normal in all regions except for the above-normal levels observed in the western Gulf of St. Lawrence (4ST) and at the Rimouski high-frequency monitoring station (4T).

Acknowledgements

We thank the staff at Fisheries and Oceans Canada's Northwest Atlantic Fisheries Centre (NWAFC) Oceanography Section, Bedford Institute of Oceanography (BIO) Ocean and Ecosystem Sciences Division (OESD), and Maurice-Lamontagne Institute (IML) Pelagic and Ecosystem Science Branch, for their acquisition, quality control and archiving of the data. We also wish to thank the efforts of the many scientific assistants and science staff at the Northwest Atlantic Fisheries Centre in St, John's, the Bedford Institute of Oceanography, the Maurice-Lamontagne Institute, and the St. Andrews Biological Station as well as the CCGS Teleost, and RRS James Cook officers and crew for their invaluable assistance at sea. The expertise of the Atlantic Reference Center in St. Andrews, and of Jackie Spry at BIO, was crucial to the completion of this work. Special thanks to Gina Doyle, Shannah Rastin, Devyn Ramsay, Brittany Pye, Steve Snook and Ryan Doody, and Wade Bailey for their important contribution to data collection, to Jean-Yves Couture, Marie-France Beaulieu, Caroline Lebel, Isabelle St-Pierre, and Caroline Lafleur from IML for preparation and standardization of the phytoplankton and zooplankton data. The data used in this report would not be available without the work of François Villeneuve and his AZMP team (Rémi Desmarais, Marie-Lyne Dubé, Line McLaughlin, Roger Pigeon, Michel Rousseau, Félix St-Pierre, Liliane St-Amand, Sonia Michaud, Isabelle St-Pierre, David Leblanc, and

Caroline Lafleur) in organizing and carrying out AZMP surveys in the Gulf region and analyzing samples. We thank Jeff Spry and Kevin Pauley for providing data from the Shediac Valley station and BIO's remote sensing unit for the composite satellite images.

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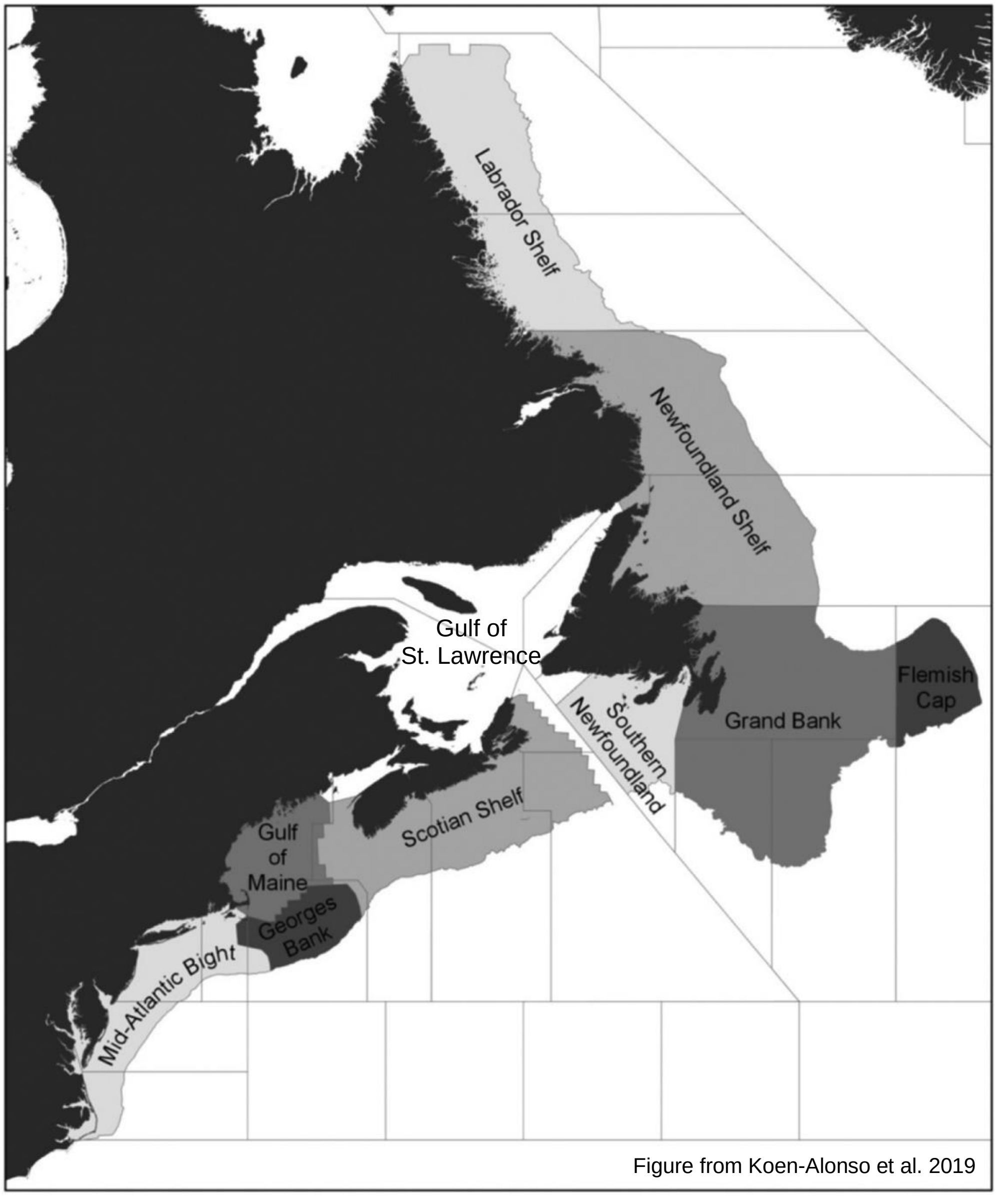

Figure 1. NAFO Ecological Production Units (EPUs) used to summarize biogeochemical oceanographic conditions and trends. The Gulf of St. Lawrence is also used as a grouping factor although it is not an official EPUs as defined by Koen-Alonso et al. 2019.

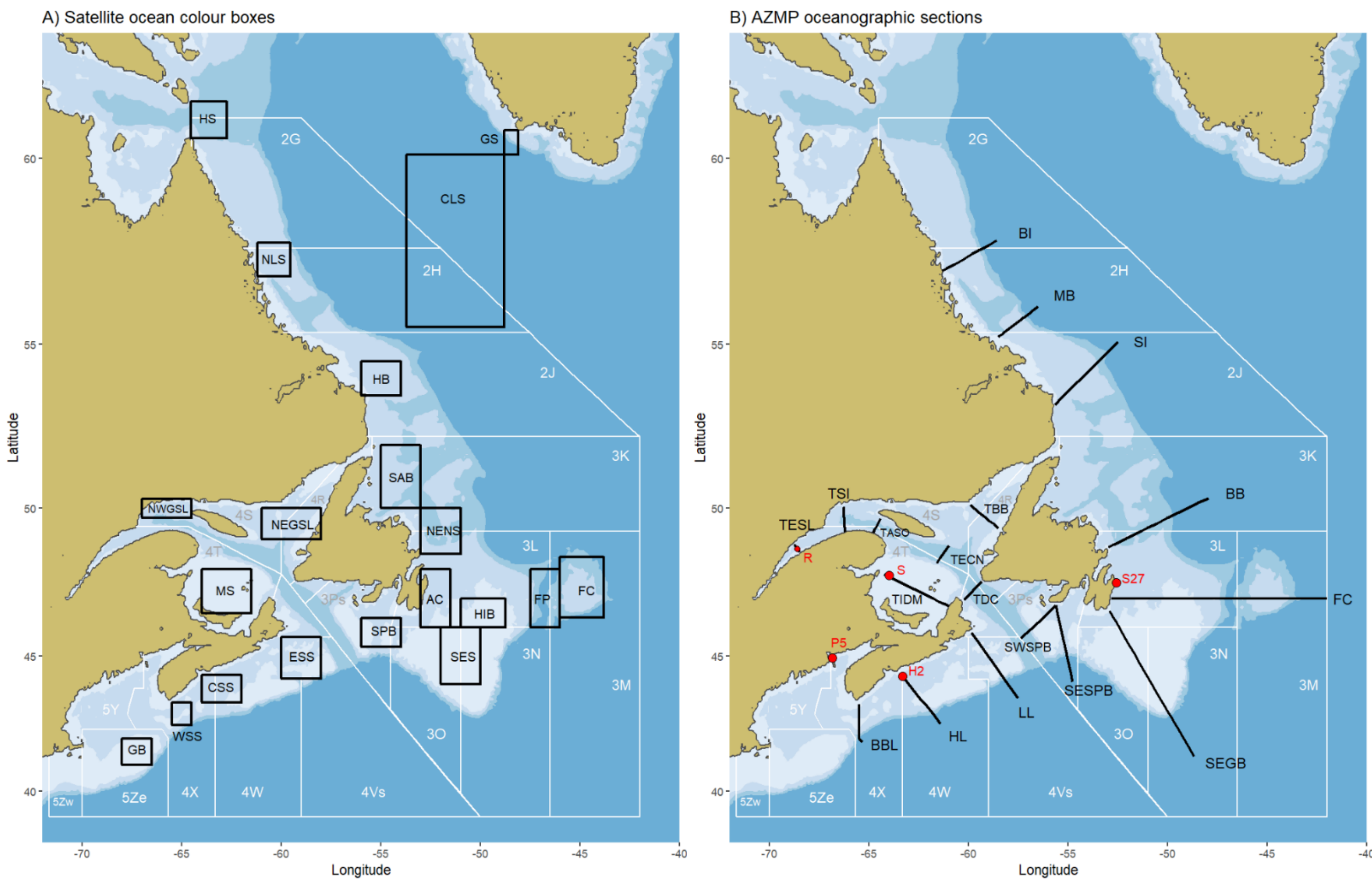

Figure 2. (A) Location of the boxes used to derive spring bloom indices (initiation, duration, and magnitude) from satellite Ocean Color imagery: (CLS=Central Labrador Sea, GS=Greenland Shelf, HS=Hudson Strait, NLS=northern Labrador Shelf, HB=Hamilton Bank, SAB=St. Anthony Basin, NENS=northeast Newfoundland Shelf, FP=Flemish Pass, FC=Flemish Cap, HIB=Hibernia, AC=Avalon Channel, 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, WB=Western Bank, 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 dots: 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.

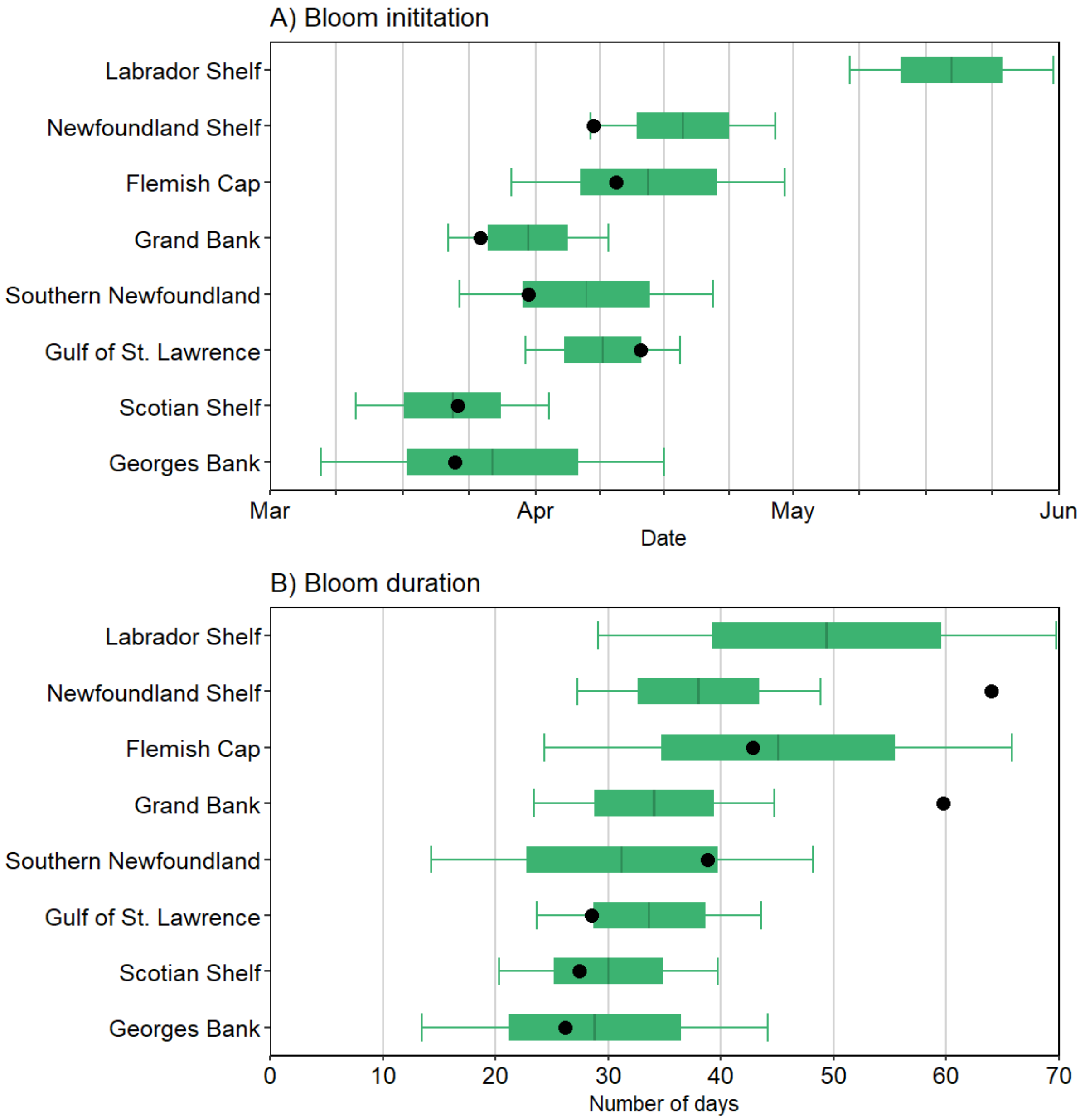

Figure 3. Phytoplankton spring bloom initiation (A) and duration (B) for seven NAFO Ecological Production Units (EPUs: Labrador Shelf, Newfoundland Shelf, Flemish Cap, Grand Bank, Southern Newfoundland, Scotian Shelf, and Georges Bank) and for the Gulf of St. Lawrence. Green boxes represent mean initiation/duration ± 0.5 SD for the 1999-2015 reference period. Error bars represent mean initiation/duration ± SD. Black dots represent spring bloom initiation/duration for the year 2019. No data were available for the Labrador Shelf region in 2019. See Figure 1 for EPUs locations.

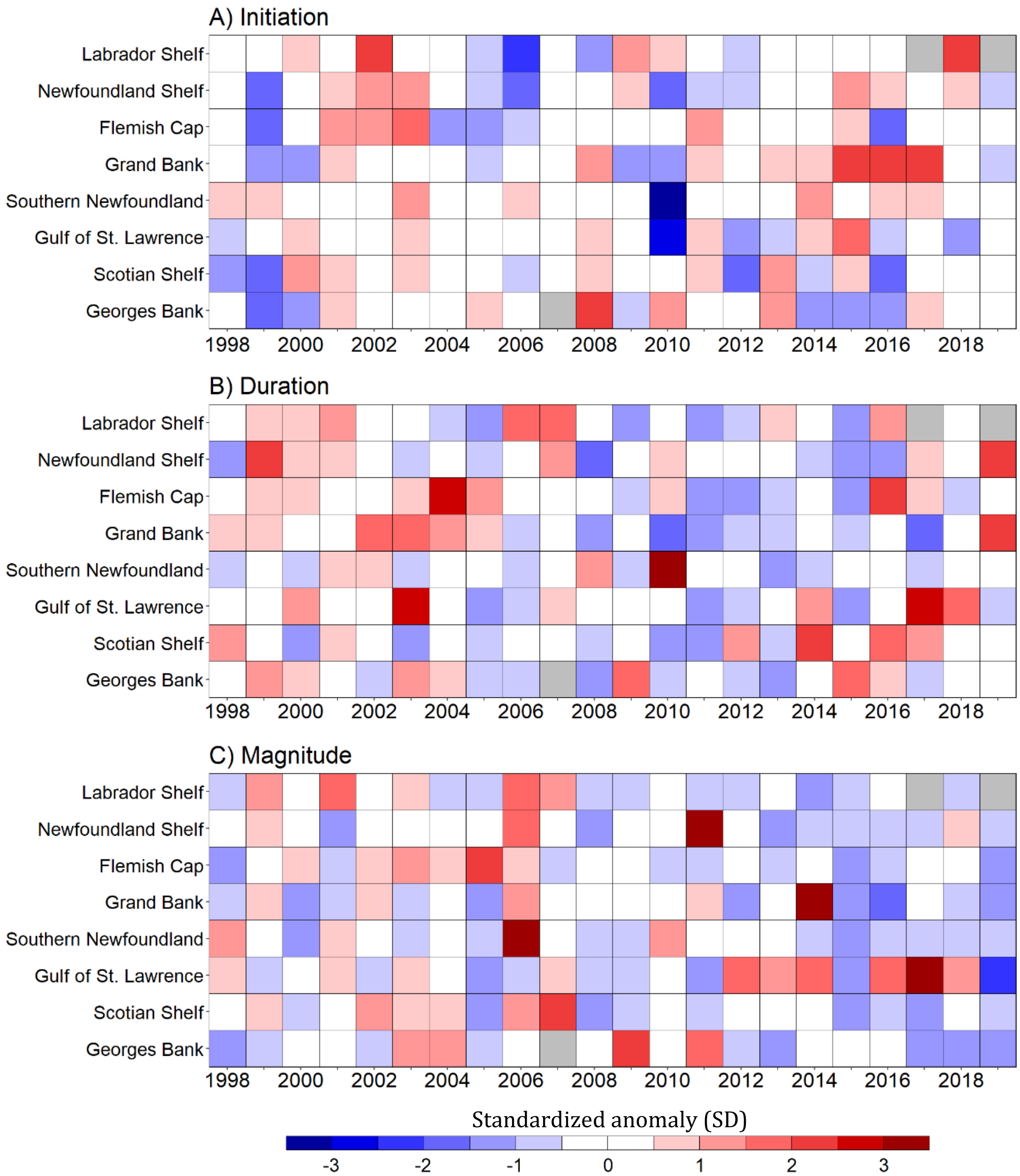

Figure 4. Annual anomaly scorecards for phytoplankton spring bloom initiation (A), duration (B) and magnitude (C) for NAFO Ecological Production Units (EPUs) and in the Gulf of St. Lawrence. Red (blue) cells indicate higher (lower) than normal conditions relative to the 1998-2015 reference period. White 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 Figure 1 for EPUs locations.

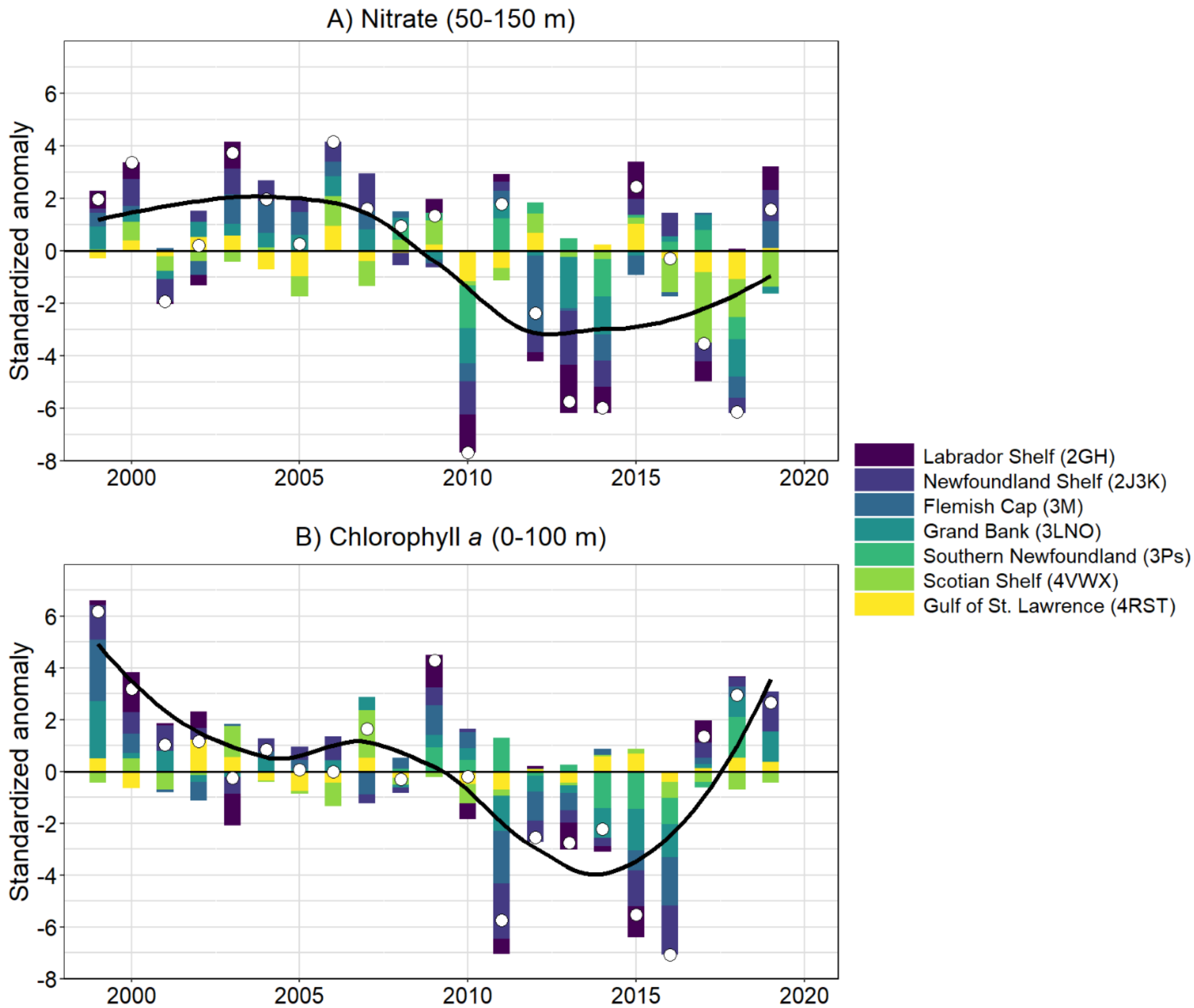

Figure 5. Anomaly time series of 50-150 m integrated nitrate (A) and 0-100 m integrated chlorophyll *a* (B) inventories in NAFO Ecological Production Units (EPUs) and in the Gulf of St. Lawrence based on a 1999-2015 reference period. White circle indicate the annual cumulated anomaly index, i.e. the sum of all anomalies for a given year. The black line is a loess regression fitted to the annual cumulated anomalies indices and represents the general large-scale temporal trend observed across NAFO Ecological Production Units (EPUs) and the Gulf of St. Lawrence. See Figure 1 for EPUs locations.

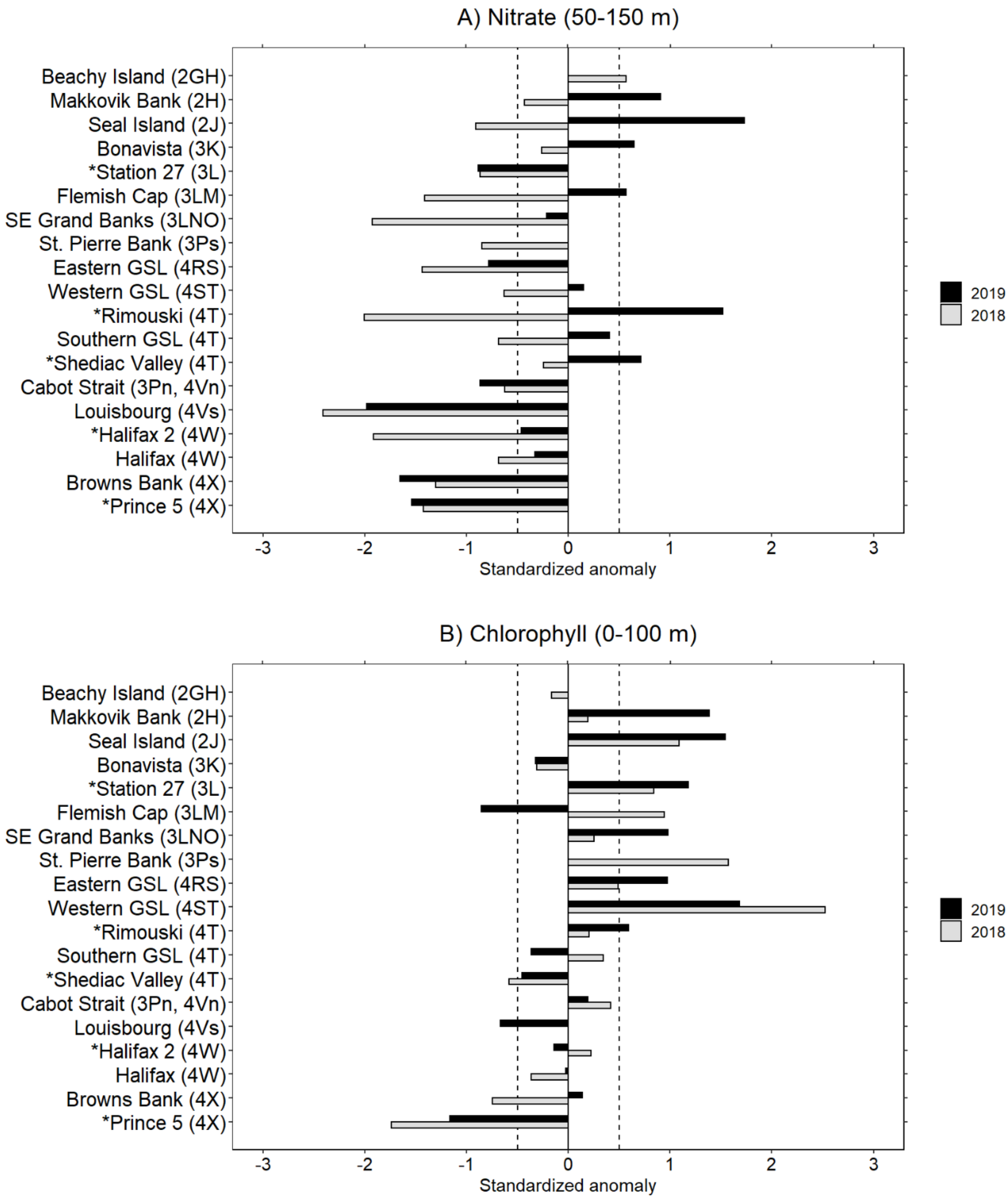

Figure 6. Comparison of seasonally corrected anomalies for 50-150 m integrated nitrate (A), and 0-100 m integrated chlorophyll *a* (B) inventories for each AZMP oceanographic sections and high-frequency monitoring stations in 2018 and 2019. Anomalies are calculated based on a 1999-2015 reference period. 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.

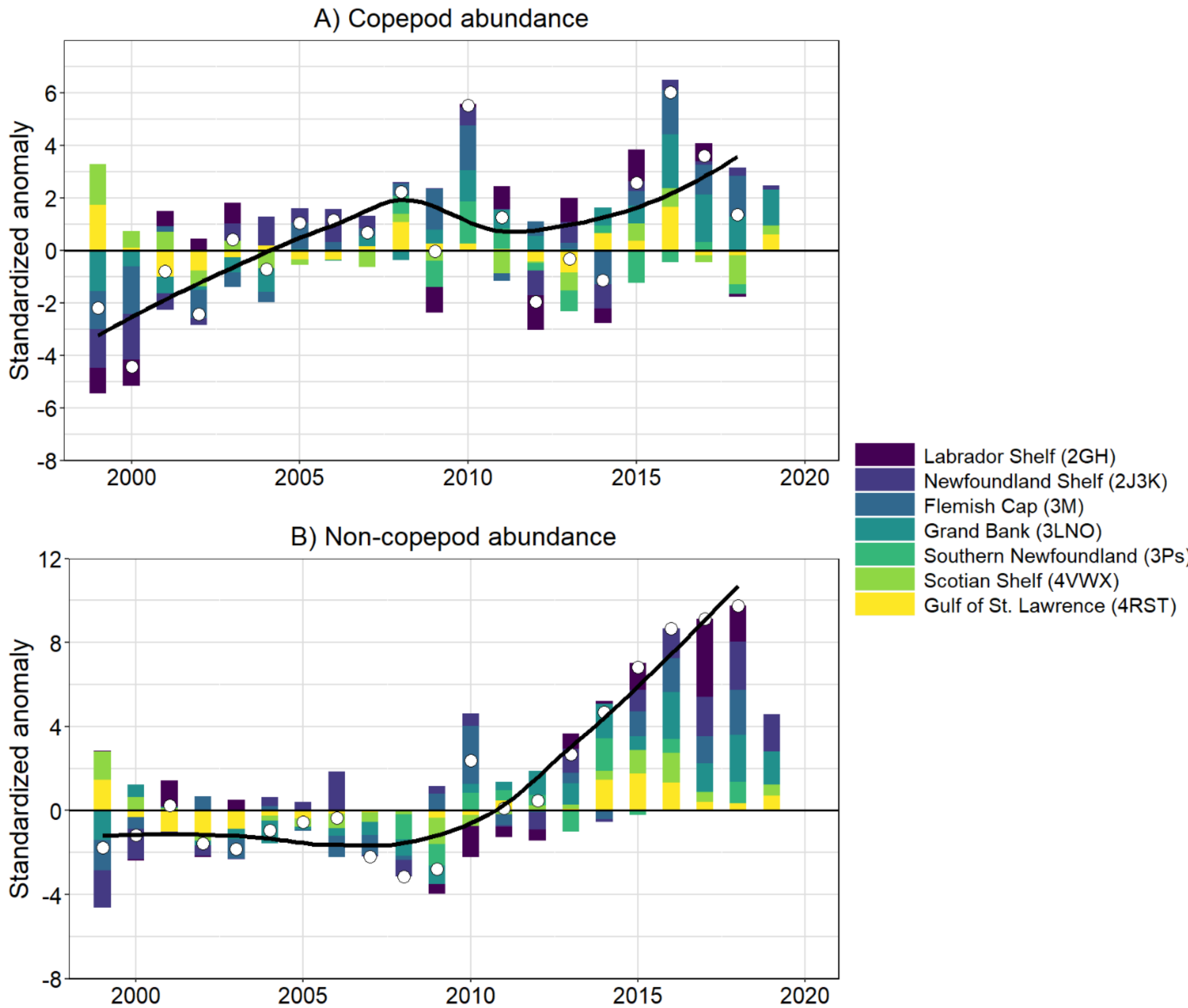

Figure 7. Anomaly time series of copepod (A) and non-copepod (B) zooplankton abundance (ind. m^{-2}) in NAFO Ecological Production Units (EPUs) and in the Gulf of St. Lawrence based on a 1999-2015 reference period. White circle indicate the annual cumulated anomaly index, i.e. the sum of all anomalies for a given year. The black line is a loess regression fitted to the annual cumulated anomalies indices and represents the general large-scale temporal trend observed across NAFO Ecological Production Units (EPUs) and the Gulf of St. Lawrence. See Figure 1 for EPUs locations.

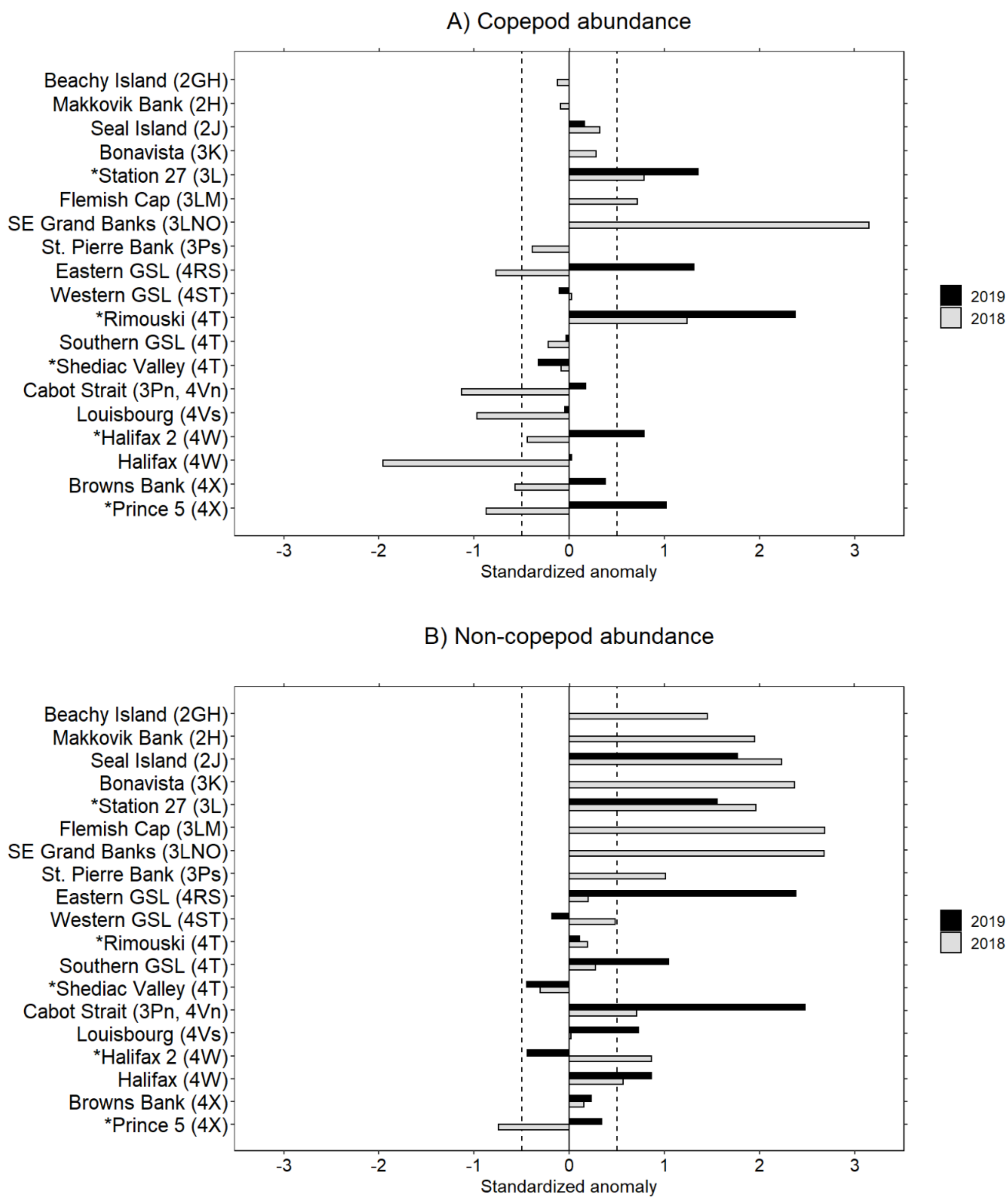

Figure 8. Comparison of seasonally corrected anomalies for copepod (A), and non-copepod (B) abundance (ind. m^{-2}) for each AZMP oceanographic sections and high-frequency monitoring stations in 2018 and 2019. Anomalies are calculated based on a 1999-2015 reference period. Anomalies within -0.5 and 0.5 (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.

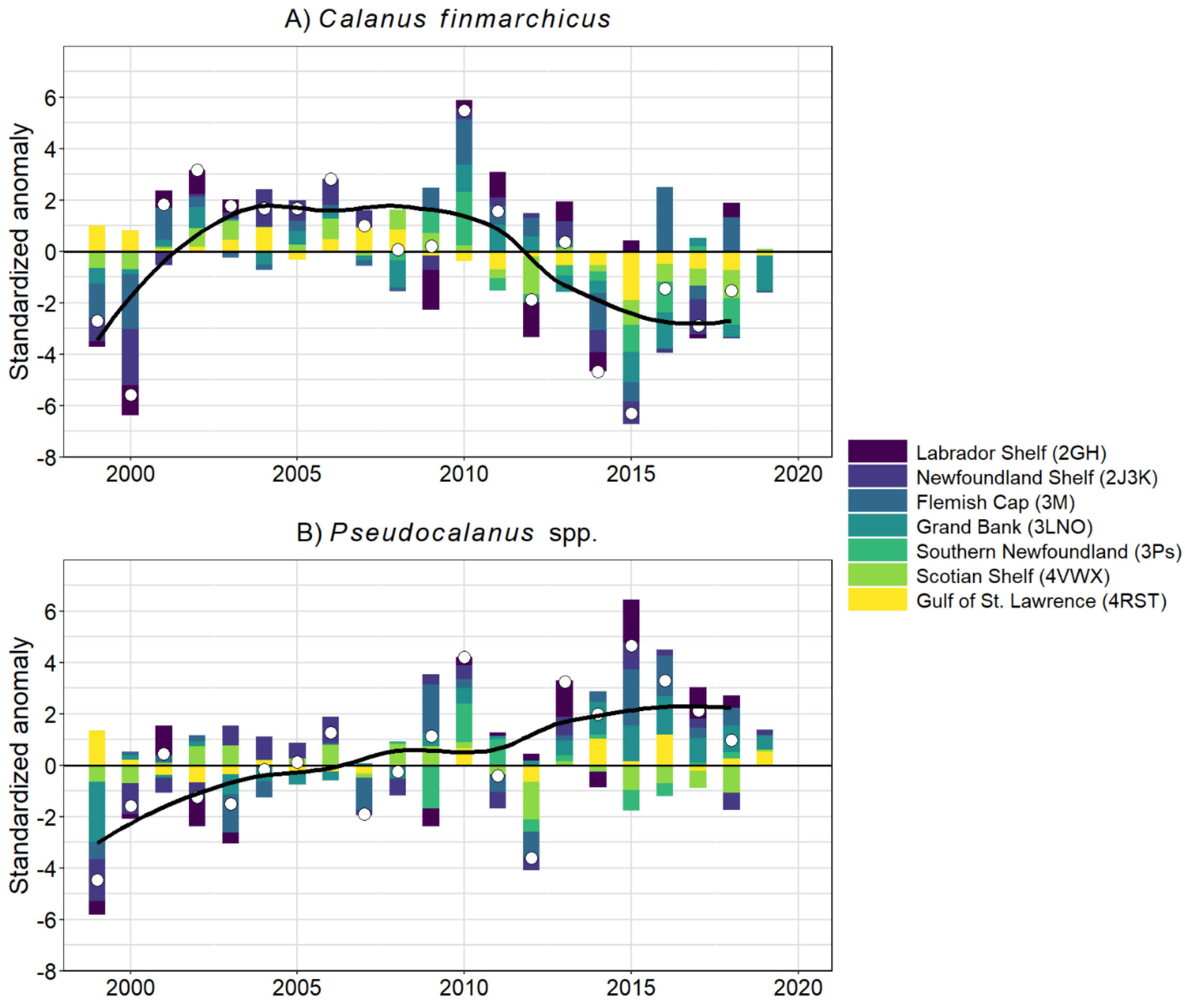

Figure 9. Anomaly time series of *Calanus finmarchicus* (A) and *Pseudocalanus* spp. (B) copepod abundance (ind. m^{-2}) in NAFO Ecological Production Units (EPUs) and in the Gulf of St. Lawrence based on a 1999-2015 reference period. White circle indicate the annual cumulated anomaly index, i.e. the sum of all anomalies for a given year. The black line is a loess regression fitted to the annual cumulated anomalies indices and represents the general large-scale temporal trend observed across NAFO Ecological Production Units (EPUs) and the Gulf of St. Lawrence. See Figure 1 for EPUs locations.

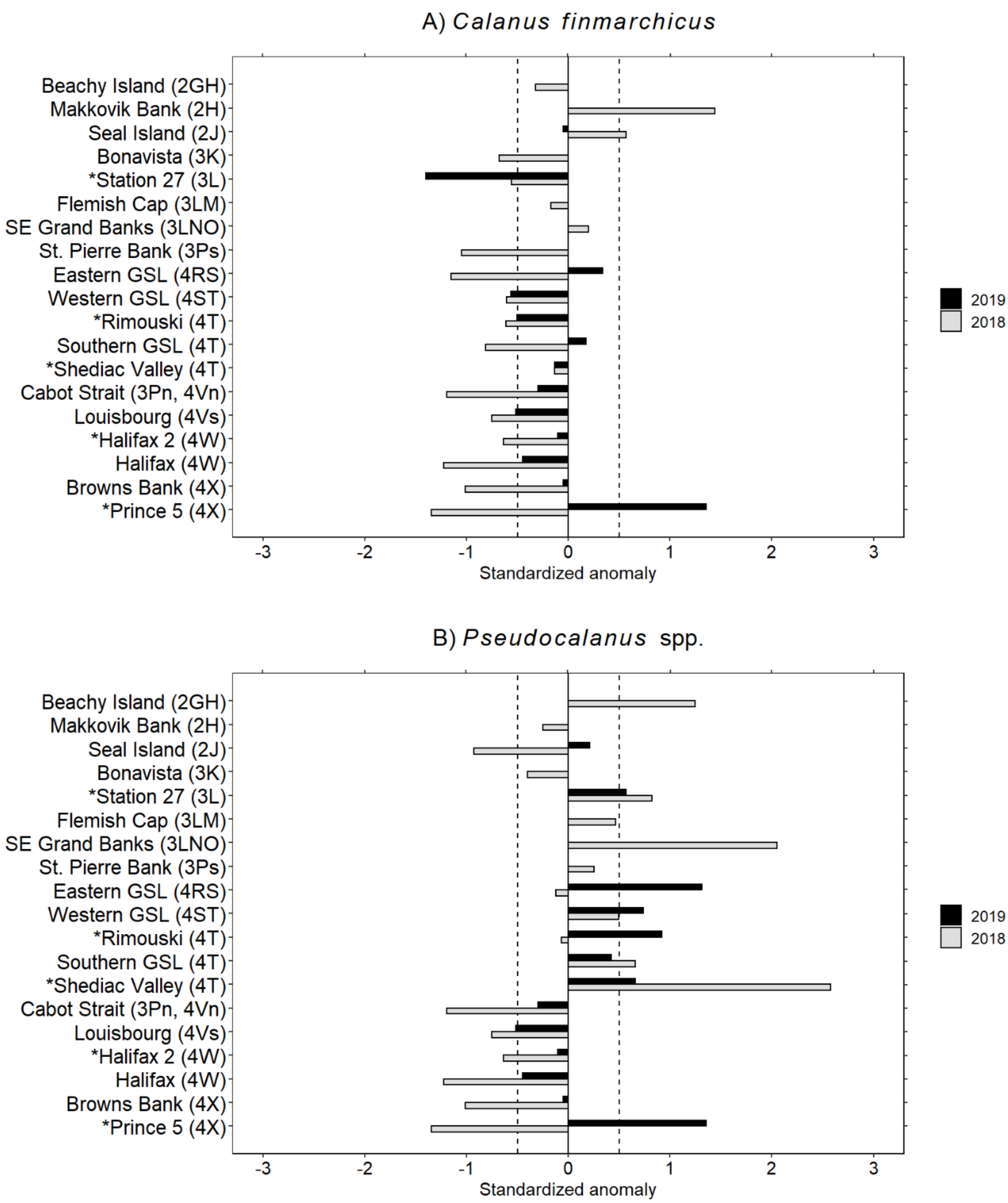

Figure 10. Comparison of seasonally corrected anomalies for *Calanus finmarchicus* (A), *Pseudocalanus* spp. (B) copepod abundance (ind. m^{-2}) for each AZMP oceanographic sections and high-frequency monitoring stations in 2018 and 2019. Anomalies are calculated based on a 1999-2015 reference period. 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.

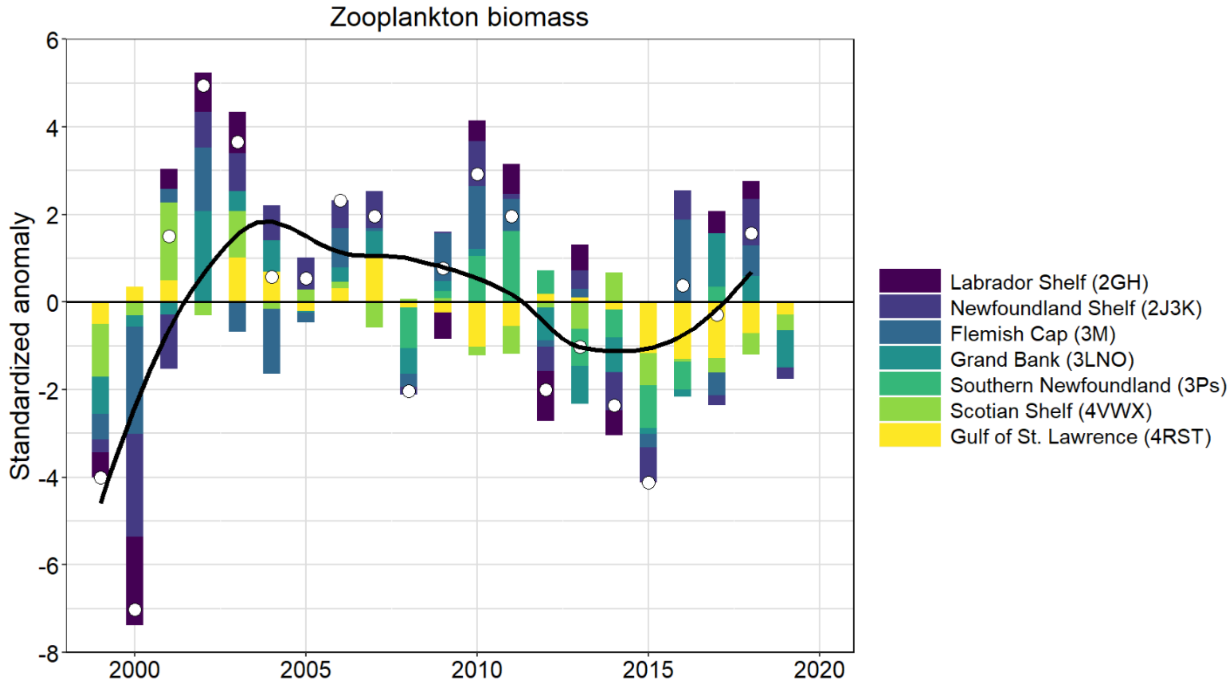

Figure 11. Anomaly time series of zooplankton biomass copepod (g dry weight m^{-2}) in NAFO Ecological Production Units (EPUs) and in the Gulf of St. Lawrence based on a 1999-2015 reference period. White circle indicate the annual cumulated anomaly index, i.e. the sum of all anomalies for a given year. The black line is a loess regression fitted to the annual cumulated anomalies indices and represents the general large-scale temporal trend observed across NAFO Ecological Production Units (EPUs) and the Gulf of St. Lawrence. See Figure 1 for EPUs locations.

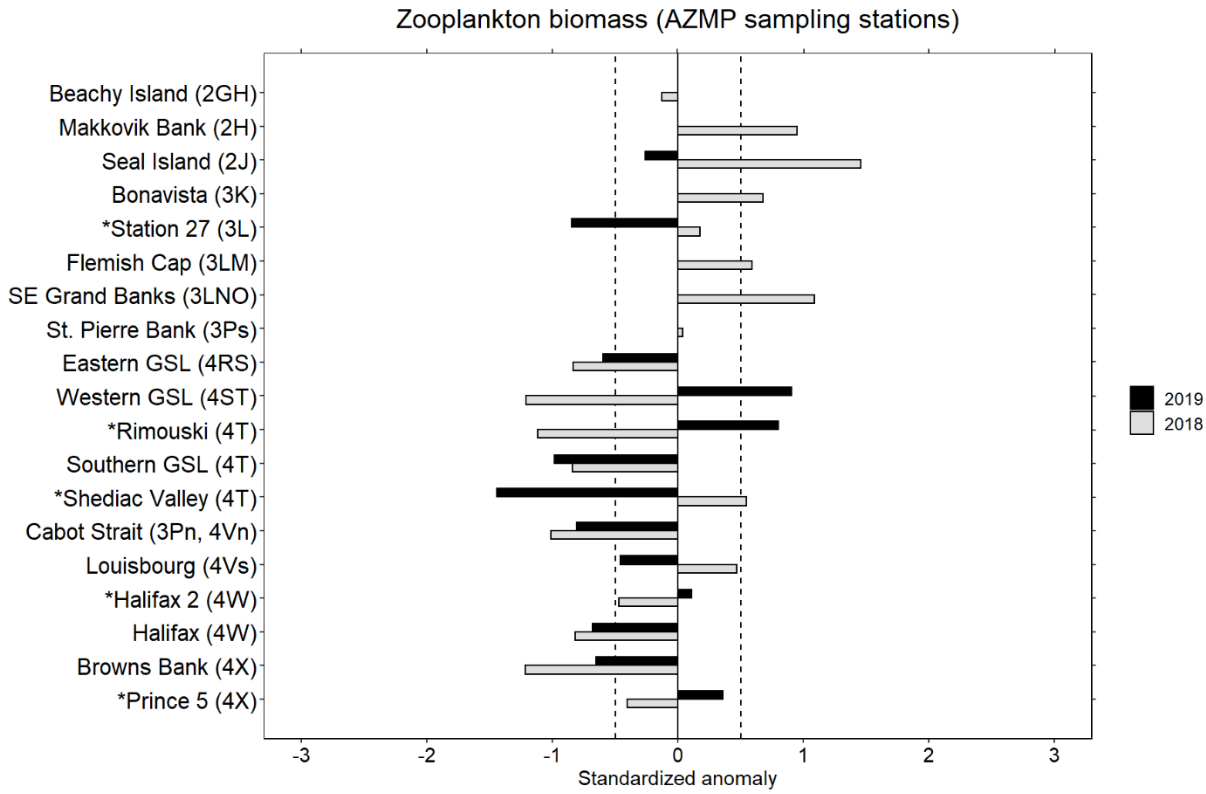

Figure 12. Comparison of seasonally corrected anomalies for zooplankton biomass (g dry weight m^{-2}) for each AZMP oceanographic sections and high-frequency monitoring stations in 2018 and 2019. Anomalies are calculated based on a 1999-2015 reference period. Anomalies within -0.5 and 0.5 (vertical dashed 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.

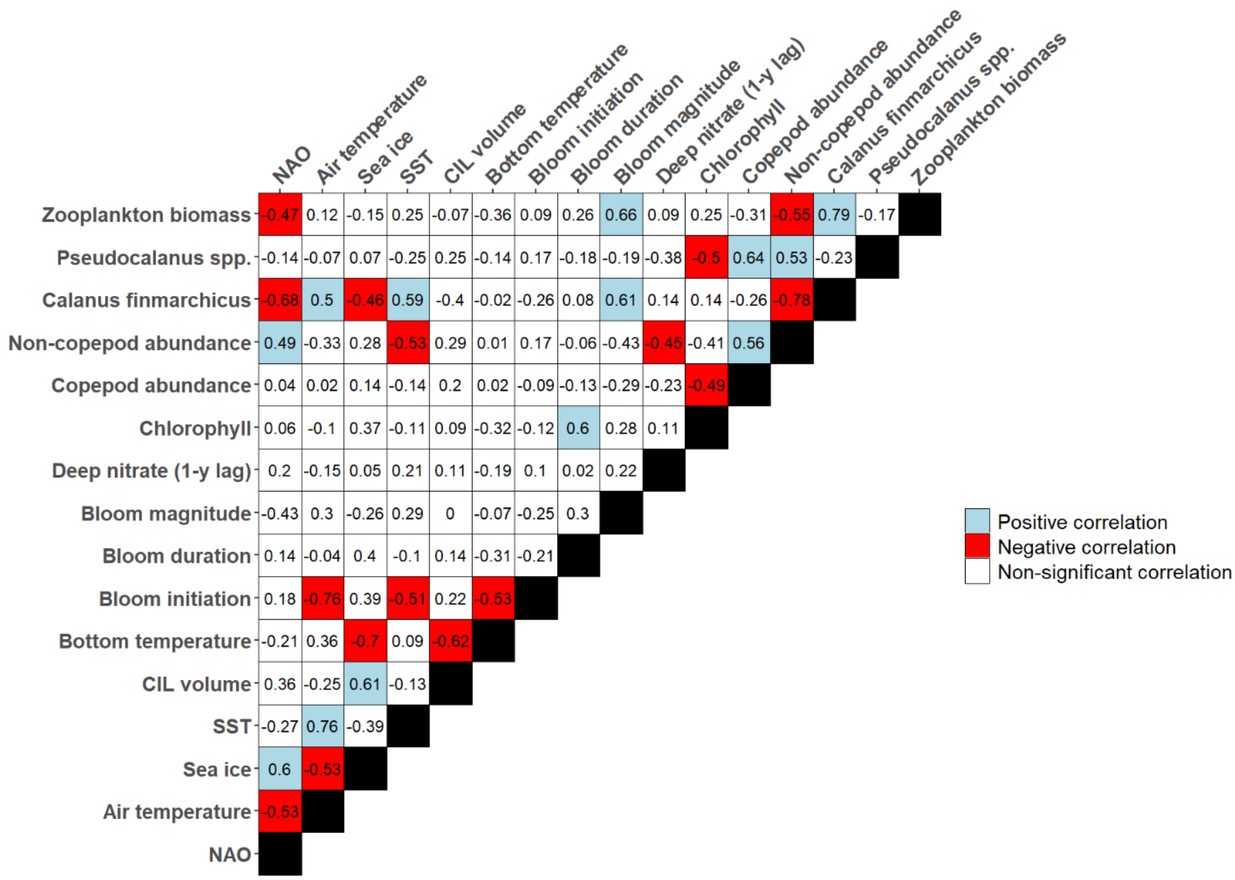

Figure 13. Summary of relationships between climatic (North Atlantic Oscillation [NAO], air temperature, sea ice cover, sea surface temperature [SST], cold intermediate layer [CIL] volume, and bottom temperature), and biogeochemical (phytoplankton spring bloom initiation, duration, and magnitude; integrated deep nitrate [50-150 m]; integrated chlorophyll *a* [0-100 m]; abundance of copepod, non-copepod, *Calanus finmarchicus*, *Pseudocalanus* spp.; zooplankton biomass) cumulated anomaly indices for the period 1999-2018. Blue 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. See Cyr et al. 2020.

Appendix 1. Corrected zooplankton biomass

Archiving errors in the DFO NL zooplankton database were discovered in 2019. Zooplankton biomass from samples collected between 2015 and 2018 at the high-frequency monitoring station S27 and during seasonal surveys were not properly corrected to account for the split fraction of the subsamples used to quantify zooplankton biomass leading to an underestimation of the biomass during that period. In addition, the thorough review of the biomass database revealed that 205 biomass samples collected between 2013 and 2015 at Station 27 (n=3) and along the Seal Island (n=20), Bonavista Bay (n=52), Flemish Cap (n=98), and Southeast Grand Bank (n=32) had not been included in the database. The omitted samples and the wrongly corrected biomass affected the climatological mean for the 1999-2015 reference period and, therefore, the biomass anomalies reported in previous NAFO SCR reports by and Bélanger et al. 2018 and Bélanger et al. 2019).

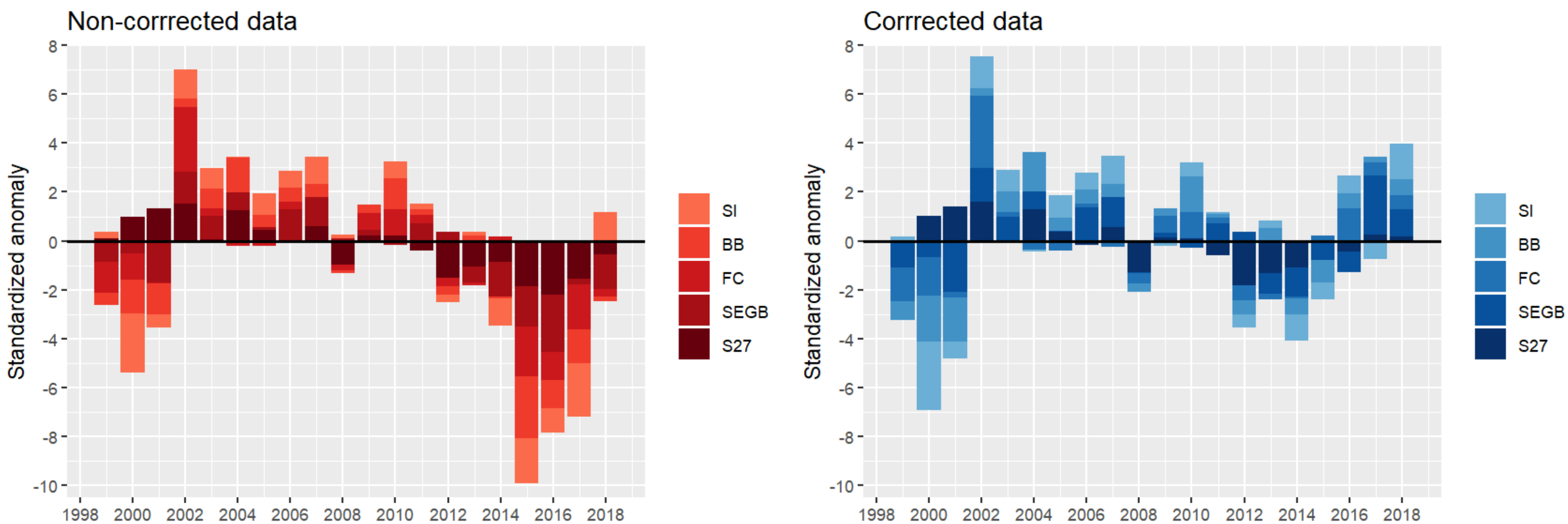

Figure A.1. Comparison of annual zooplankton anomalies between non-corrected (left panel) and corrected (right panel) biomass data for the coastal high-frequency monitoring station (S27) and the oceanographic sections (SI: Seal Island, BB: Bonavista Bay, FC: Flemish Cap, SEGB: Southeast Grand Bank). See figure 1 for geographical location of the sampling station and sections