Physical controls and ecological implications of the timing of the spring phytoplankton bloom on the Newfoundland and Labrador shelf

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Context

Large phytoplankton blooms occur every spring in mid- and high-latitude oceans. Blooms provide abundant food for higher trophic levels and many species have adapted their development to benefit from it at crucial stages of their life cycle. Substantial changes in the timing of the bloom may impact the energy transfer to higher trophic levels and, in turn, ecosystem productivity. Understanding bloom dynamics is thus a key step in our understanding of an ecosystem, especially in the context of climate change. In this study we demonstrate that the ocean climate, the timing of the bloom and the abundance of a key zooplankton species change in synchronicity following decadal cycles.

Introduction

The Newfoundland and Labrador (NL) shelf and the Grand Banks of Newfoundland have been known as iconic fishing areas for centuries. In such areas with seasonal sea ice coverage, the timing of the spring bloom has been linked to sea ice melting, which stratifies the water columns and promotes favorable conditions for phytoplankton to grow and accumulate. With sea ice gradually disappearing as a result of climate change, we revisited the physical drivers controlling the initiation of the spring bloom in the region. We found that the timing of the phytoplankton bloom on the Grand Banks corresponds to the timing of ocean re-stratification following winter mixing. We also found that large-scale climate indicators are good proxies for the timing of the bloom and the abundance of Calanus finmarchicus, a key zooplankton species for the ecosystem.

1. Large decadal variability of the NL climate

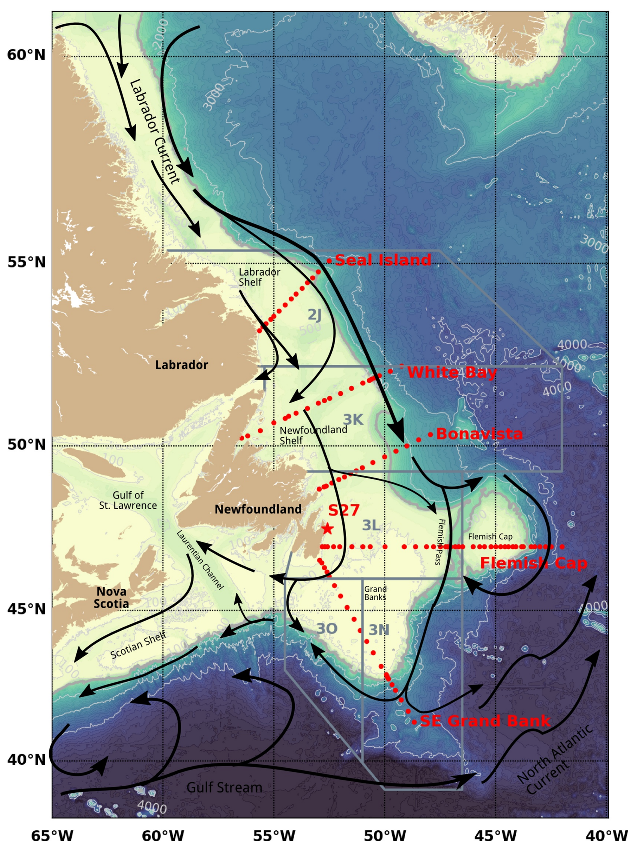


Figure 1. The NL shelf is monitored as part of the Atlantic Zone Monitoring Program (AZMP; Therriault et al., 1998). Northwest Atlantic Fisheries Organisation (NAFO) Divisions on the NL shelf are drawn in black. Some components of the AZMP used to derive the NL Climate index (Figure 2)are shown. The hydrographic sections Seal Island, Bonavista Bay and Flemish Cap are shown with red dots. Long-term hydrographic Station 27 is highlighted with a red star. The shelf break is delimited by a thicker and darker contour corresponding to the isobath 1000m (used to clip the SST and bottom temperature).

The NL shelf undergoes large decadal climate variability. The NL Climate Index (NLCI; Cyr and Galbraith, 2021) captures this variability.

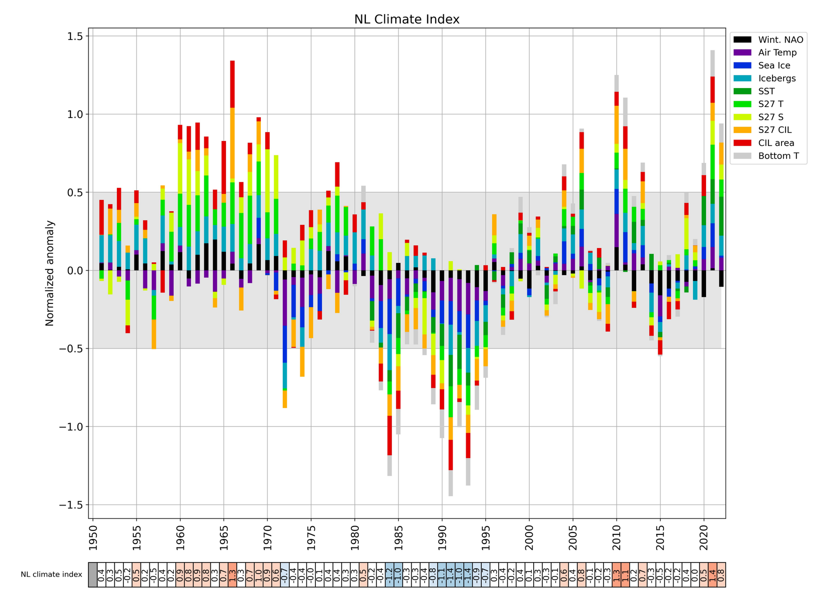


Figure 2. The NL climate index (NLCI) is the average of 10 subindices represented in a stacked-bar fashion. Here the total length of the bar is the average of the respective subindices in which their relative contribution to the average is adjusted proportionally. The scorecard at the bottom of the figure shows the colour-coded numerical values of the NLCI. The time series used to construct the NLCI have been choosen to be relatively independent to each other. These time series are the following (see Figure 1 for some geographical locations):
- winter NAO index (starts in 1951),
- the air temperature at five sites (starts in 1950);
- the sea ice season duration and maximum area for the northern Labrador, southern Labrador and Newfoundland shelves (starts in 1969);
- the number of icebergs (starts in 1950);
- sea surface temperatures in NAFO Divisions 2GHJ3KLNOP (starts in 1982);
- vertically averaged temperature and salinity at Station 27;
- CIL core temperature at Station 27 (starts in 1951);
- the summer CIL areas on the hydrographic sections Seal Island, Bonavista and Flemish Cap (starts in 1950); and
- spring and fall bottom temperatures in NAFO Divisions 3LNOPs and 2HJ3KLNO, respectively (starts in 1980).

The sign of some indices (NAO, ice, icebergs, salinity and CIL volume) has been reversed when positive anomalies are generally indicative of colder conditions. Grey cells in the scorecards indicate the absence of data.

2. Stratification and the timing of the phytoplankton spring bloom

The spring bloom occurs when the water column reached its minimum stratification (or in other words when the ocean re-stratifies). We can predict the timing of the spring bloom over the entire NL shelf using stratification at Station 27 (Figure 5).

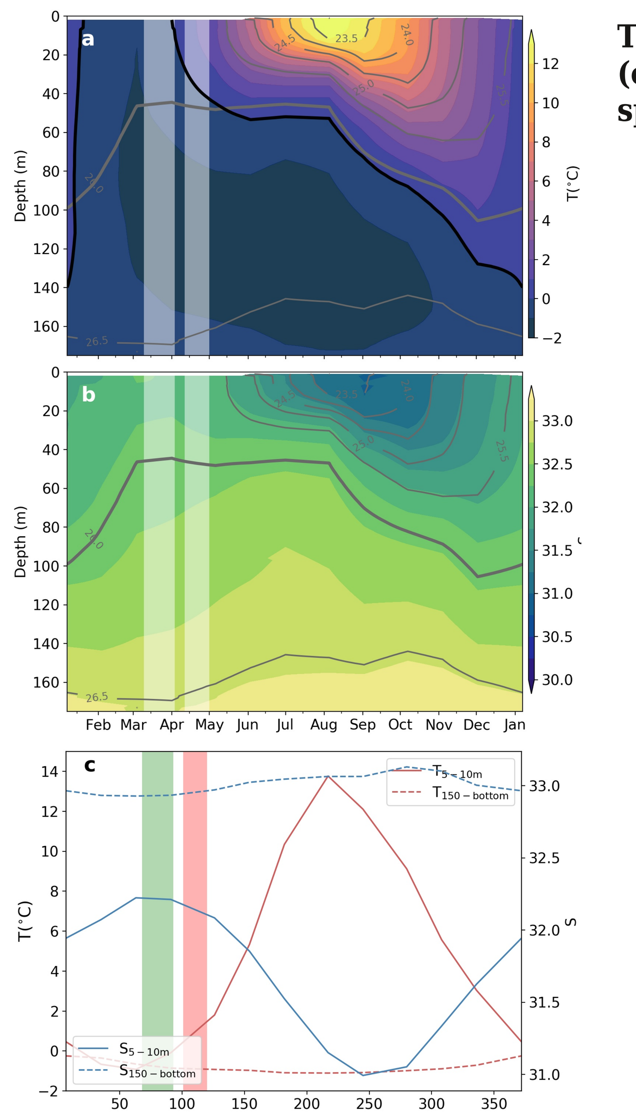


Figure 3. Climatological (1991-2020) seasonal evolution of temperature (a) and salinity (b) fields at Station 27. Gray contours in both panels represent the density (σ_0), with the isopycnal σ_0 = 26.0 kg m^{-3} highlighted with a thicker contour. The thick black contour on the top panel represent the 0°C isotherm. The average temperature (red) and salinity (blue) between 5-10 m (solid lines) and 150 m-bottom (dashed lines) at Station 27 are shown in panel (c). The vertical green and red bands (and corresponding gray bands in panels a and b) represent the climatological (1998-2020) start (±1 sd) and peak (±1 sd) of the spring bloom, respectively, derived from Modis and SeaWiFS sensors (see Table 1).

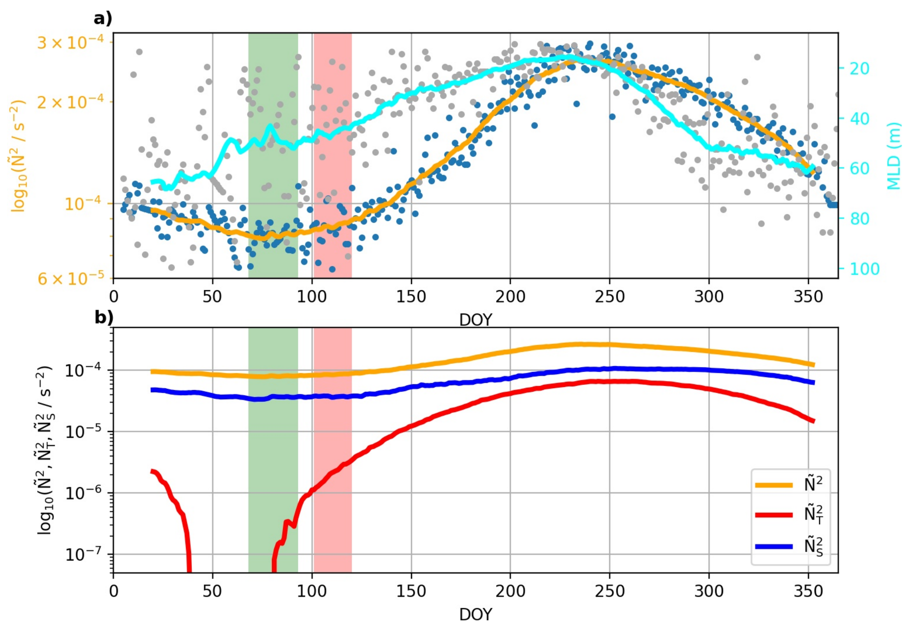


Figure 4. Climatological (1991-2020) seasonal evolution of the stratification at Station 27 for each day-of-the-year (DOY).
a) The dark blue dots are the daily climatological values of the stratification, while the orange curve is a 30-day moving average through these points. The dark gray dots are the daily climatological values of the MLD, while the light blue curve is a 30-day moving average smoothing within these points.
b) The red and blue curves are respectively the temperature and salinity contributions to the stratification (orange curve; same as in panel a). The vertical green and red bands in both panels represent respectively the climatological (1998-2020) timing of the initiation and peak production (±1 sd) of the spring bloom in 3LNO derived from Modis and SeaWiFS sensors (see Table 1).

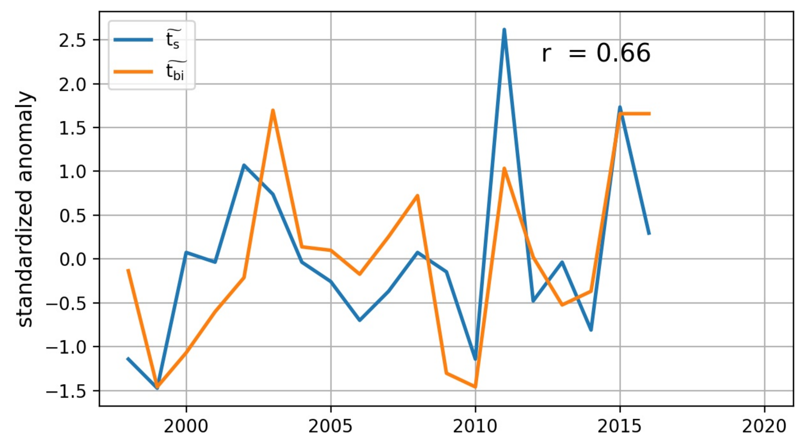
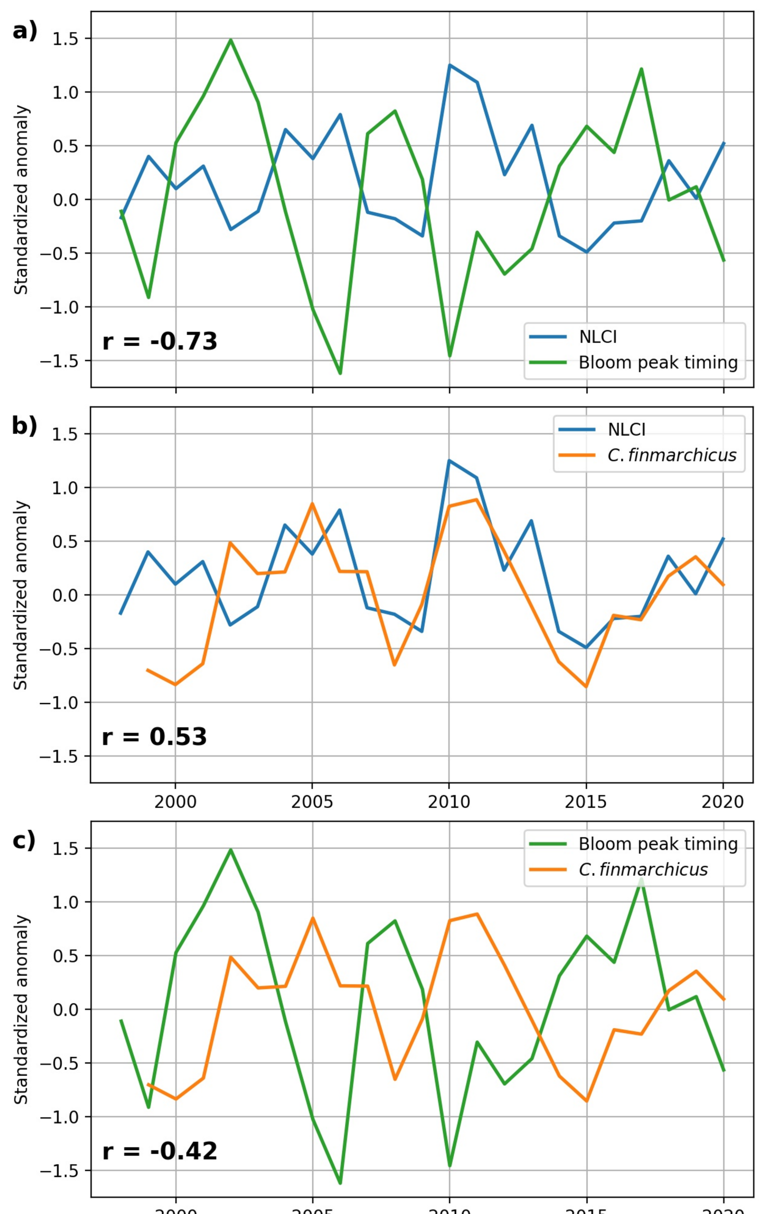


Figure 5. Time series of the standardized anomalies of the initiation of the spring bloom in 3LNO from Modis and SeaWiFS sensors (orange curve) and the timing of the minimum stratification at Station 27 (blue curve; see Appendix A for calculation). The Pearson correlation coefficient (r) is indicated on the figure.

Region	Bloom initiation (DOY)	Peak production (DOY)
2J	116 ± 21	152 ± 14
3K	95 ± 10	130 ± 10
3L	88 ± 11	115 ± 9
3LNO	82 ± 12	112 ± 10

Table 1. Mean timing (and standard deviation) of the spring bloom initiation and peak for different NAFO divisions over 1998-2004. See Appendix 2 for calculation.

3. Climate, bloom and secondary production



Cycles of milder and colder winters generally occur on decadal time scales on the NL shelf. Cold winters are usually accompanied by delayed springs, colder ocean temperatures and the presence of heavy sea ice. In contrast, milder winters are generally synonymous with early sea ice retreat and fresher ocean conditions.

These climatic cycles, which also influence the timing of the spring re-stratification, are well captured by the NLCI (Figure 2).

A robust negative correlation is found between the NLCI and the timing of the spring bloom on the NL shelf (panel a).

The NLCI and the timing of the bloom are good predictor of the biomass of Calanus finmarchicus (panels b and c), a key zooplankton specie for the NL ecosystem.

Overall, the ocean climate, the timing of the spring bloom and the zooplankton biomass evolve in relative synchronicity over decadal periods.

Figure 6. From the NL climate to the timing of the bloom and the abundance of zooplankton between 1998 and 2020. The Pearson correlation coefficients between the curves in each panel (r) is shown.
a) Comparison between the Newfoundland and Labrador Climate Index (NLCI; Cyr and Galbraith, 2021) in blue and the standardized anomaly of the timing of the bloom peak concentration averaged over NAFO divisions 2J, 3K and 3LNO in green.
b) Comparison between the NLCI (blue) and the abundance of Calanus finmarchicus copepods averaged over 2J, 3K and 3LNO (in orange; starts in 1999).
c) Comparison between the standardized anomaly of the timing of the bloom peak from panel a (green) and the abundance of Calanus finmarchicus copepods from panel b (orange).

4. Implication of climate change for the timing of the bloom

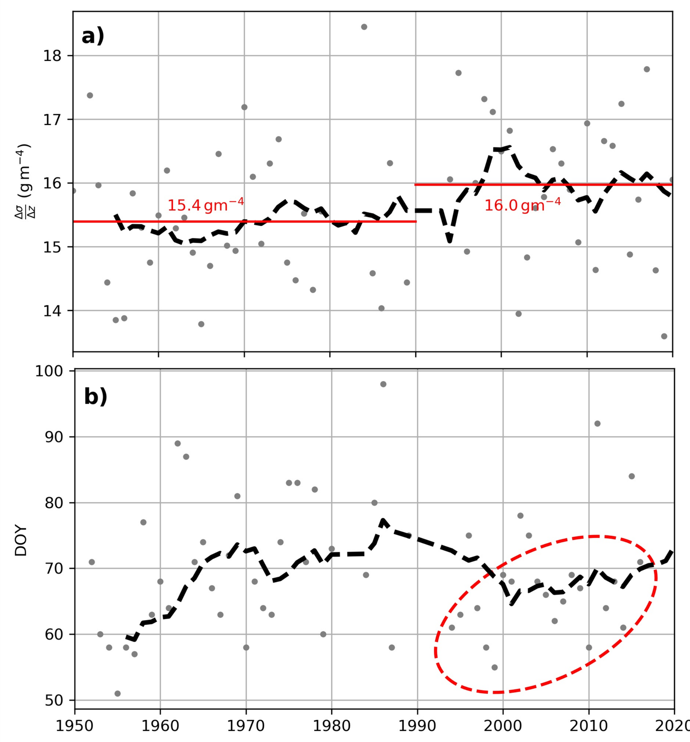


Figure 7. Interannual evolution (1950-2020) of stratification and timing of the re-stratification
a) Annual mean density difference (5-150 m) at Station 27
b) Day-of-the-year (DOY) when the minimum stratification is reached.
The gray dots in both panels are the annual values and the thick dashed line corresponds to a 10-year moving average (average of current and previous 9 years; up to 5 data points can be missing). The two red lines in panel a correspond the the averaged density difference for the periods 1950-1990 and 1991-2020, respectively. The red-dashed ellipse in panel b highlights a period of particularly early blooms between the late 1990s and the early 2010s.

The world's oceans are becoming increasingly stratified as a result of anthropogenic climate change, with potential negative ramifications for the world ecosystems (Pörtner et al., 2019).

Stratification at Station 27 has increased by 3.9% between 1950-1990 and 1991-2020, a number in relative agreement with that of the global ocean*.

Despite important decadal changes, we did not find any significant trends in the timing of the re-stratification (and thus in the prediction of the spring bloom) on the NL shelf.

Earlier blooms however occurred in a cluster of years in the the late 1990s / early 2000s (dashed-red ellipse). This, combined with a documented delayed capelin spawning after 1991 (Murphy et al., 2021) may have exacerbated the mis-match between this key species for the ecosystem and food availability, and thus promoted the continued low productivity of the stock and of the NL ecosystem as a whole since the early 1990s.

***2.3±0.1% for the top 200 m of the water column occurred between 1971-1990 and 1998-2017 (Pörtner et al., 2019)**

Appendix 1. Timing of re-stratification

The timing of ocean re-stratification is calculated as the minimum of a quadractic fit on weekly density stratification and further compared with the initiation of the bloom from both SeaWiFS (dashed blue) and MODIS (dashed black). The interannual evolution of the standardized anomalies of the timing of the re-stratification is presented in Figure 5.

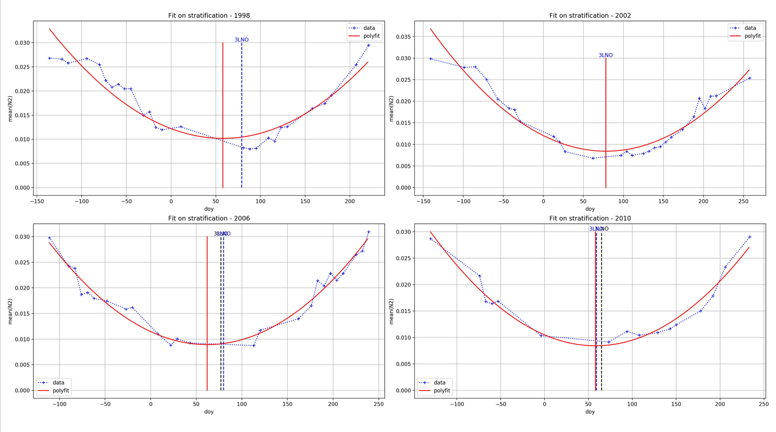


Figure A1. Examples of fit for the stratification (defined here as the density difference between 5 and 150m) for 4 selected years. The timing of the minimum stratification (vertical red line) is defined as the date of the minimum obtained from a quadratic fit (red) on the weekly stratification at Station 27 (blue). The timing of the spring bloom derived from MODIS (dashed-black) and/or SeaWIFS (dashed-blue) are indicated.

Appendix 2. Bloom timing and secondary production

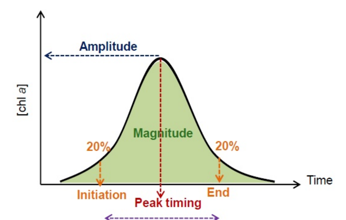


Figure A2. Satellite imagery (4-km resolution) of ocean color was used to characterize the phenology of the spring phytoplankton bloom for the shelf portion of Northwest Atlantic Fisheries Organization (NAFO) divisions 2J, 3K and 3LNO (Figure 1). We used the R Shiny application PhytoFit (Clay et al., 2021) to calculate the initiation and peak timing of the bloom based on daily mean chlorophyll a (chl-a) concentrations retrieved from composite images of reflectance data from SeaWiFS (1998-2010) and MODIS (2003-2020).

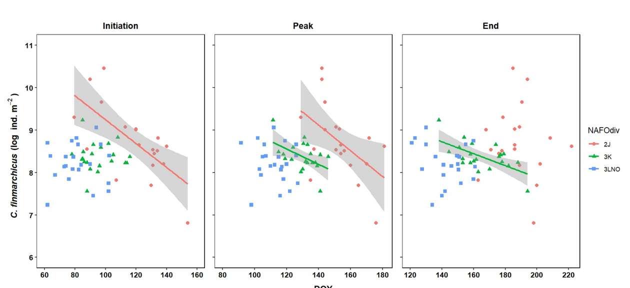


Figure A3. Relationship between the abundance of Calanus finmarchicus and the timing of the phytoplankton spring bloom initiation (a) peak (b) and end (c) in NAFO divisions 2J, 3K and 3LNO. The linear fits (ordinary least squares), including the 95% confidence interval in a gray shade, have been drawn where the trend is significant. This figure suggests that the timing of the bloom impacts the secondary production differently between the north and the south of the NL shelf.

Conclusion

Phytoplankton spring blooms annually trigger a complex trophic cascade through the marine ecosystem. In certain ways, they are metronomes of the environment in the sense that many species have adapted their life cycles, or migration patterns, in order to benefit from the improved feeding opportunities they provide. Any change to the timing of these blooms can potentially have dire consequences for the productivity of a given ecosystem.

In this study, we show that the bloom on the Grand Banks of Newfoundland begins shortly after the minimum stratification in late winter. We developed a simple stratification index that is a good proxy for the timing of the bloom derived by satellites (r=0.66; 44% of variance explained). We also show that the NL climate index also predicts with great success the timing of the bloom and the abundance of Calanus finmarchicus over the NL shelf as a whole (53% and 28% of the variance explained, respectively). The fluctuations of the NL climate, and thus the timing of the bloom and the abundance of this key zooplankton species, vary on decadal time scales. Simple proxies that predict changes in the base of the marine food web will naturally aid the development of ecosystem-informed models for species at higher trophic levels. Such advances are needed to move towards an ecosystem approach to fisheries management and adapt to a changing climate.

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