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Temperature or Nutrients? Changes in Diatom Abundance and Diatom/Dinoflagellate Ratio during Marine Heat Waves in Tofino Inlet, British Columbia, Canada from 2013 to 2023

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Temperature or Nutrients? Changes in Diatom Abundance and Diatom/ Dinoflagellate Ratio during Marine Heat Waves in Tofino Inlet, British Columbia, Canada from 2013 to 2023

Cover Page Footnote

ACKNOWLEDGMENTS This research could not have been possible without the support of Clayoquot Biosphere Trust for funding boat time on the R/V Beach Hopper and Captain Toby Theriault for taking us sampling. The UWT Mary Cline award for funding the rental of an SUV that provided transportation to the sampling site in Tofino, BC Canada. The Ahousaht First Nation and the Maaqutusiis Hahoulthee Stewardship Society for allowing us to sample in their territorial waters.

Abstract

Diatoms are a major group of phytoplankton that form the foundation of aquatic food webs and dominate the phytoplankton community in aquatic systems. With silica-based cell walls and no flagella, their mobility is limited, and their demand for silica is greater than that of dinoflagellates and other groups. As climate change drives rising ocean temperatures and more frequent marine heat waves (MHWs), studies in the Northeastern Pacific show that diatom abundance relative to dinoflagellates declines during these events. Two main published hypotheses that explain this are: 1) Dinoflagellates are more tolerant to temperature, and 2) Silicate availability may decrease with warming, disadvantaging silica-dependent diatoms. This study will investigate diatom abundance in relation to temperature and silicate changes in Tofino Inlet, Clayoquot Sound, on Vancouver Island's west coast (2013–2023), a period that included several MHWs. Researchers from the University of Washington Tacoma have collected annual late-summer/early fall water property data in Clayoquot Sound since 2001, along with phytoplankton samples since 2006. This dataset includes CTD profiles (temperature, salinity, density, oxygen, fluorescence, transmissivity), discrete water samples (nutrients, phytoplankton), and 10-meter vertical net tows (20 µm mesh). As the foundation of the food web, changes in phytoplankton composition can have drastic impacts on higher trophic levels. Understanding how MHWs affect phytoplankton communities will help improve climate change preparedness for marine resource managers. This study did not find a correlation between diatom abundance relative to silicate or temperature in Tofino Inlet. However, a spatial pattern was found in silicate concentrations along the inlet.

Keywords: phytoplankton, environmental science, capstone, climate change, marine heat waves

Introduction

Phytoplankton form the base of the marine food web. Showing incredible diversity, these microscopic organisms come in various shapes and sizes, having different nutrient and habitat requirements. Three main groups exist: the diatoms, dinoflagellates, and phytoflagellates, also called nanoflagellates due to their small size. This study focused on diatoms and dinoflagellates. Diatoms are primary producers (photoautotrophs) that photosynthesize using the sun as their primary source of energy. Diatoms also incorporate silica into their cell walls, forming hard lattice frameworks called frustules, and are at the mercy of the currents to move them around as they are not motile (Strickland 2018). In contrast, dinoflagellates, a second phytoplankton group, do not utilize silica in their cell walls and have a flagellum (essentially a whip-like tail) that allows these phytoplankton to move through the water column under their own power. This group can photosynthesize (photoautotrophic), some can also eat other organisms (heterotrophic), and some can do both (mixotrophic), which makes these phytoplankton extremely adaptable. Prior research has shown that diatoms have a higher nutrient requirement and a narrower temperature range tolerance than dinoflagellates (Feng et al. 2021; Xiao et al. 2018). This puts diatoms at a disadvantage as the climate changes.

A consequence of climate change has been marine heat waves (MHW), periods of extreme heat in the ocean (Peña et al. 2018). These events are projected to occur more regularly, last longer, and strengthen as global warming continues (NOAA 2024). The first major marine heat wave in the Pacific Northwest was “the Blob” from 2014 through 2016 (NOAA 2019a). During this event, hotter water came into the coast from

the ocean and raised ocean temperatures as much as 4° C in some places (Peña et al. 2018). Fish and sea bird die-offs were associated with this warming, which many attribute to compositional shifts in the base of the food web (NOAA 2019a). A trend has been seen in some locations with diatom to dinoflagellate ratios changing as MHWs occur (Arteaga and Rousseux 2023). The exact change varies depending on the normal state of the region; for example, estuaries in the Southwestern Pacific Ocean had a noticeable increase in diatoms compared to dinoflagellates, whereas estuaries in the Northeastern Pacific had a decrease in diatoms (Arteaga and Rousseux 2023; Cheung et al. 2021; Du and Peterson 2018).

While these shifting patterns in phytoplankton communities have been observed across various coastal regions, one place where long-term monitoring offers an opportunity to examine these effects on a coastal estuary is Tofino Inlet—a glacially carved fjord in Clayoquot Sound that has been the focus of ongoing research at the University of Washington Tacoma (UWT) for over two decades (Fig. 1). Water property data, nutrients, and phytoplankton data have been collected in Clayoquot Sound every year, barring a few exceptions, in early September by UWT researchers. This investigation uses this data set to examine the two main hypotheses proposed for the observed decrease in diatom abundance in the Northeastern Pacific Ocean during times of marine heat waves: 1) Dinoflagellates are more tolerant to temperature, and 2) Silicate availability may decrease with warming, disadvantaging silica-dependent diatoms.

Methods

For the purposes of this study, data from 2013, 2014, 2017, 2018, 2019, 2022, and 2023 were used. Discrete water samples for phytoplankton and nutrients were not collected in Tofino Inlet in 2015 and 2016, and due to COVID restrictions, no discrete water sampling was performed in 2020 and 2021. CTD (conductivity, temperature, and depth) data was collected in all years 2013-2023 in Tofino Inlet (Table 1).

At every station, profiles of temperature were collected using a SeaBird 19 Conductivity-Temperature-Depth (CTD). This instrument records conductivity, temperature, salinity, density, dissolved oxygen, fluorescence, and transmissivity continuously as it descends in the water column. Once retrieved from the instruments and processed, the temperature data for this project was extracted using R code for further analysis. Temperature was later plotted with silica to qualitatively inspect the relationship between the two variables for any correlations (Fig. 11); the same was done for temperature and diatom/dinoflagellate abundance (Fig. 13). Longitudinal contour sections were created using Surfer software for each year from 2013 to 2023 to view the spatial distribution of temperature in the inlet over time (Figs. 17-27).

At select stations, nutrient samples were collected at the water's surface (approximately 1m) with a Thoreson bottle and at the bottom with a Niskin bottle attached to the CTD rigging (Table 1). These samples were then filtered through a .45-micron filter before being frozen (Fig. 2b). The frozen samples were sent to the University of Washington Seattle's Marine Chemistry Laboratory for analysis. This laboratory uses a SEAL AA3 Autoanalyzer to analyze for PO_4 (phosphate), SiOH_4 (silicate), NO_3 (nitrate), NO_2 (nitrite), and NH_4 (ammonia) concentrations. For this

study's purpose, only the silicate concentration was of interest. Silicates at both the bottom and surface in μM was plotted separately over time by station (Figs. 3, 4, 9, and 10), against temperature (Fig. 11), and against diatom abundance (Fig. 13). Additionally, the two MHW years plus the most recent year were spatially mapped using ArcGIS Pro (Figs. 14-16) to qualitatively examine correlations.

Phytoplankton samples were collected in three ways at four stations in Tofino Inlet: two discrete samples at the surface and thermocline (the point of rapid temperature drop with increasing depth) using a Thoreson bottle, and a highly concentrated inventory sample using a $20\mu\text{M}$ mesh 10m vertical net tow. This net tow concentrates the phytoplankton present in the first 10m of the water column, allowing a more complete inventory of the phytoplankton community compared to the discrete samples. All phytoplankton samples were fixed with 1 ml of 37% formaldehyde (formalin) in the field. Once in the lab, the surface and thermocline samples were allowed to settle completely before being decanted to the 10 ml. Net samples were not decanted and counted unconcentrated. All phytoplankton samples were loaded onto a 0.1 ml Palmer-Maloney slide before being systematically identified and enumerated using an Olympus BX compound microscope at 200x. Phytoplankton were identified to genus and species when possible, and the number of individuals of each species was recorded. For the discrete phytoplankton samples, the concentration of phytoplankton in cells/L was calculated. Due to sample methods, this is not possible for the net tow samples.

The phytoplankton concentration values were combined from all years in the study range and sorted into three groups: diatoms, dinoflagellates, and others. The

sorted data was graphed against temperature, bottom and surface silica, and time to qualitatively analyze it for trends and correlations.

Silicates at both the bottom and surface, the average temperature over the first 10m of the water column, and phytoplankton abundances by group were graphed together to assess for any overarching patterns or correlations (Fig. 13).

Results and Discussion

Neither the hypothesis that dinoflagellates are more tolerant to temperature nor the hypothesis that silicate availability may decrease with warming, disadvantaging silica-dependent diatoms, was supported by the data from this study.

No correlations are seen when comparing the average temperature over the first 10m of water at each station to the silicate concentration (Fig. 11). Higher bottom silicate tends to be associated with colder water. The two coldest points (both surface and bottom) occurred at station 59 in 2022 and are most likely due to upwelling, a phenomenon where colder, nutrient-rich waters are driven up to the surface due to wind patterns driving ocean currents offshore from the coast (Fig. 11). In terms of overall silicate patterns, a spatial trend exists, with surface silicate being highest around the mouth of the inlet (station 59) and decreasing as you go up the inlet (station 51) (Fig. 3). The opposite pattern can be seen in the bottom silicate, with levels being lowest at the mouth of the inlet and highest at the head (Fig. 4).

Our current hypothesis is that the double sills of Tofino Inlet prevent new water from coming all the way in from the ocean. Fjords have been carved by glaciers, which leave behind piles of rock debris as underwater ridges, forming shallow subsurface sills that act as barriers to deep water flow. This would prevent surface silicate from being

replenished and leave deceased diatoms trapped at the bottom of the inlet, unable to be flushed out entirely, thus increasing bottom silicate. Given that the pattern can be seen across all inlets (Figs. 5 and 6), our double sill hypothesis would explain why Tofino Inlet has comparatively more silicate at the bottom, but not the pattern itself.

This also aligns with previous research by Chanda Hanson (2021), which indicated that Tofino Inlet had significantly higher levels of silicate at the bottom near the head of the inlet compared to other inlets (Figs. 5 and 6). While the mechanism for the spatial pattern of silicate appears to be shared across all inlets in Clayoquot Sound, Tofino Inlet appears to be more severely impacted due to its second sill. More research is needed to determine whether this is the exact cause or if another mechanism exists, such as the sediment from the freshwater river at the head of Tofino Inlet being high in silicate. Temporally, the bottom silicate at station 51 appears to have decreased (Fig. 10). While this station still has the highest concentration among the four, its total concentration has noticeably declined when comparing 2013 to 2023. Silicate appears to vary from year to year with no overall trends seen (Figs. 9 and 10). Maps of the spatial distribution of surface and bottom silicate for the marine heat wave years 2014 and 2019, as well as the most recent sampling year 2023, are shown in figures 14-16.

Looking at the average temperature in the first 10m over time, a small but noticeable spike can be seen during the marine heat wave in 2019 (Fig. 12). However, temperature does appear to remain within a two-degree range, with few exceptions, and does not show any positive or negative trends. This is surprising given the marine heat wave of 2014 through 2015 and the sharp increase in ocean temperatures associated with this event (Peña et al. 2018). When examining the longitudinal contour sections,

the initial occurrence of the 2014 marine heat wave is evident (Fig. 18), along with the subsequent warming observed in 2015 and 2016 (Figs. 19 and 20). The water then experiences a slight cooling (Figs. 21 and 22), before a second marine heat wave takes place in 2019 (Fig. 21). Following this second heat wave, the water temperature has continued to decline, but as of 2023 has not returned to its pre-2014 marine heat wave levels (Fig. 27).

No linear changes in diatom and dinoflagellate percentages were observed (Figs. 7 and 8). Although the exact percentages vary each year, it is evident that a decrease in diatoms corresponds with an increase in dinoflagellates. This relationship was most pronounced at station 55 in 2018 and station 51 in 2022 (Figs. 7 and 8). It is surprising that a more noticeable change is not observed during marine heatwave years, as the decrease in diatom abundance during these events has been documented at other locations in the Northeastern Pacific Ocean (Arteaga and Rousseux, 2023). Past students have reported changes in phytoplankton diversity through fluctuations in Simpson's Diversity Index values (Mortenson 2021) and the ratio of diatoms to dinoflagellates (Barry 2018); however, when examining diatom abundance alone, no significant changes were noted. While a change in phytoplankton community composition was not observed, an overall decrease in phytoplankton was noted from 2017 to 2018 (Fig. 13). The precise cause of this decrease remains unknown.

Conclusion

Tofino Inlet presents a unique opportunity for studying phytoplankton responses to marine heat waves. The distinct bathymetry of the inlet, along with its history of sampling, makes it an ideal site for future research. At the time of this paper, diatom

abundance in Tofino Inlet does not appear to be significantly impacted by marine heat waves, unlike those in other sounds of the Northeastern Pacific. This enables research into potential mechanisms that could help enhance the resilience of phytoplankton communities. Alarming, while no specific changes in diatom abundance are observed, there is a notable decline in overall abundance that occurs after 2017. This shift necessitates further investigation and should be a priority for future research, as such a dramatic decrease in phytoplankton could have significant implications for the stability of the marine food web in this inlet. As climate change advances, marine heat waves and overall ocean temperature increases are expected not only to persist but also to become more frequent, longer-lasting, and more extreme. It is essential to understand how these events affect phytoplankton at the base of the food web, as disruptions at this level could lead to instability in the entire food web and potentially result in significant consequences for higher trophic levels.

Tables and Figures

	Station Number									
Year	59	58	57	45	55	48	54	53	52	51
2013	C, N	C	C, N	C, N, P	C, N, P	C	C, N	C, N	C	C, N, P
2014	C	C	C, N	C, N, P	C, N, P	C, N	C	C, N	C	C, N, P
2015		C	C	C	C	C	C	C		C
2016	C	C	C	C	C	C	C	C	C	C
2017	C	C	C	C	C	C	C	C	C	C
2018	C, N, P	C	C, N	C, N, P	C, N, P	C, N	C, N	C, N	C	C, N, P
2019	C, N, P	C	C, N	C, N, P	C, N, P	C, N	C, N	C, N	C	C, N, P
2020	C	C	C	C	C	C	C	C	C	C
2021	C	C	C	C	C	C	C	C	C	C
2022	C, N, P	C	C, N	C, N, P	C, N, P	C, N	C, N	C, N	C	C, N, P
2023	C, N, P	C	C, N	C, N, P	C, N, P	C, N	C, N	C, N	C	C, N, P

Table 1. List of Tofino Inlet stations with associated samples taken each year. C stands for CTD sample, N for nutrients, and P for phytoplankton.

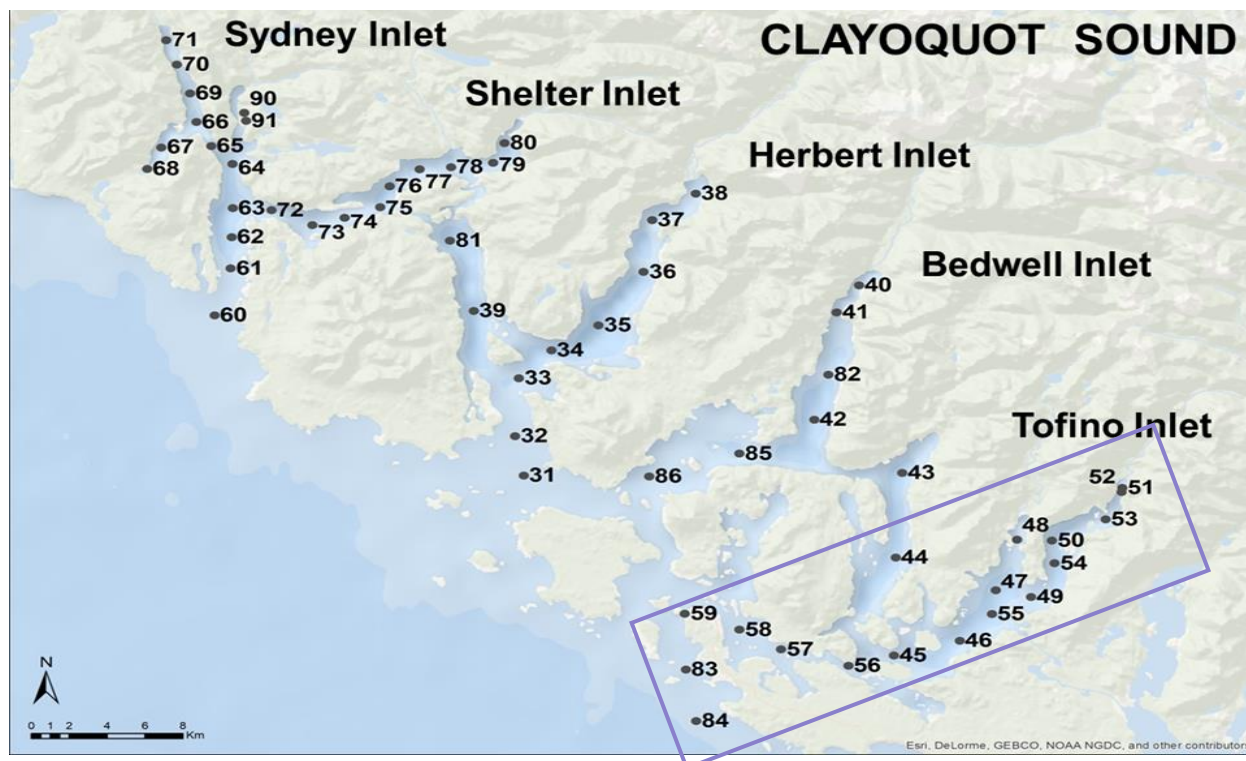


Figure 1. Map of Clayoquot Sound, BC, Canada with station numbers overlayed. Tofino Inlet is shown in a purple rectangle.



Figures 2a & 2b. Field sampling on the R/V Beach Hopper in Clayoquot Sound, BC, Canada, September 2024. Figure 1 shows a triggered Thoreson bottle being hand-hauled into the boat. Figure 2 shows nutrient samples being syringe filtered into a sample bottle.

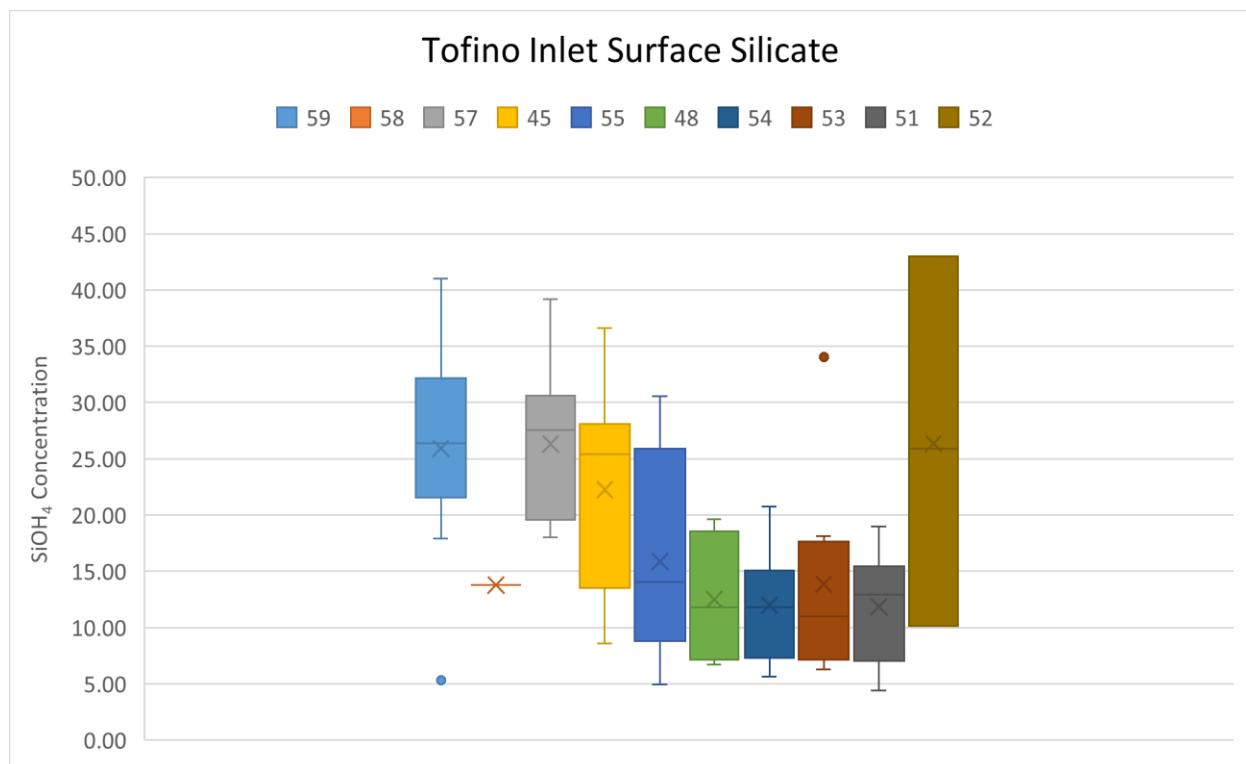


Figure 3. Range of surface silicate concentrations from 2013 to 2023 at each station in Tofino Inlet from the mouth to the head.

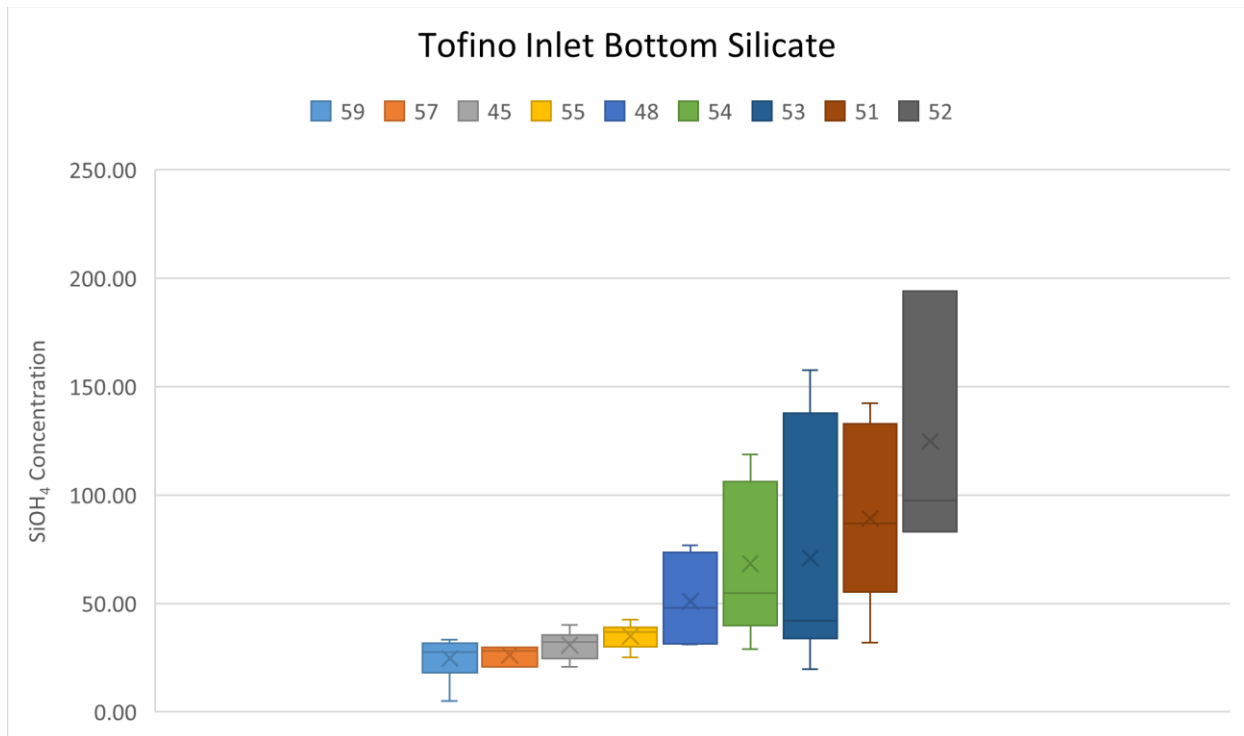


Figure 4. Range of surface silicate concentrations from 2013 to 2023 at each station in Tofino Inlet from the mouth to the head.

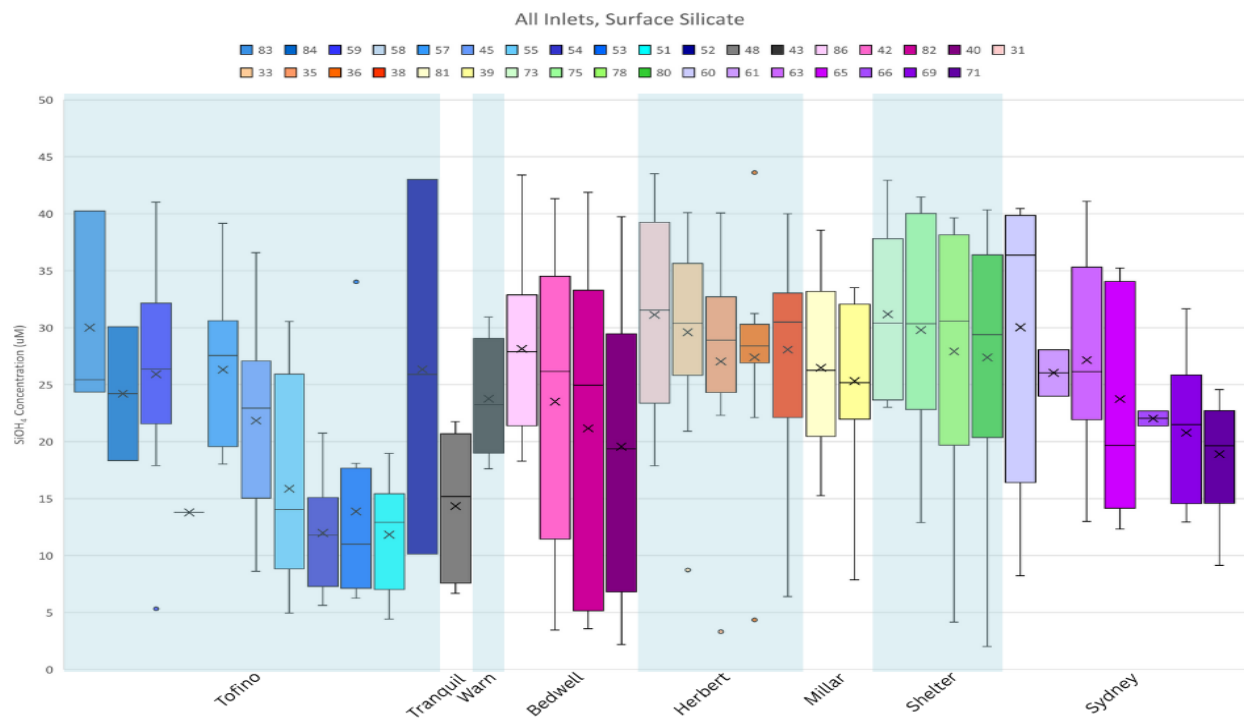


Figure 5. Range of surface silicate concentrations from 2013 to 2023 at each station in Clayoquot Sound, stations are arranged from the mouth to head, and inlets are arranged from the southernmost inlet to the northernmost inlet. The blue boxes are to help denote each inlet.

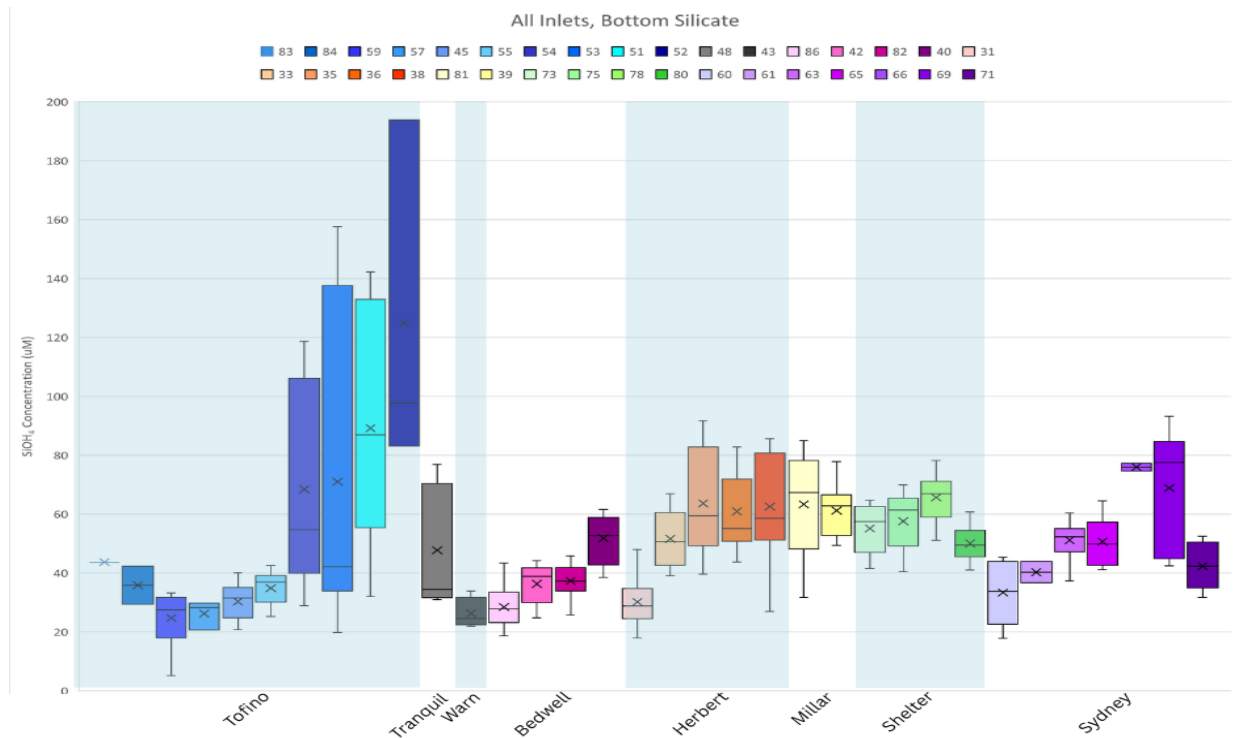


Figure 6. Range of bottom silicate concentrations from 2013 to 2023 at each station in Clayoquot Sound, stations are arranged from the mouth to head, and inlets are arranged from the southernmost inlet to the northernmost inlet. The blue boxes are to help denote each inlet.

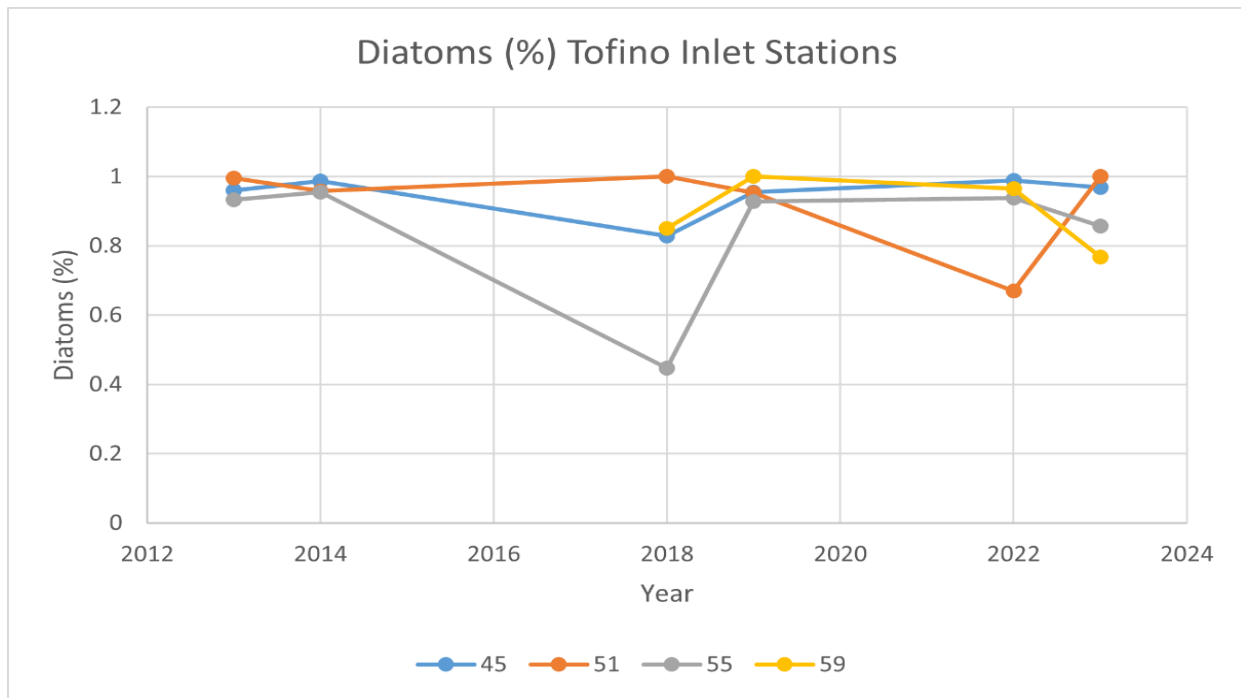


Figure 7. Percent of phytoplankton community made up of diatoms by station per year for Tofino Inlet 2013-2023.

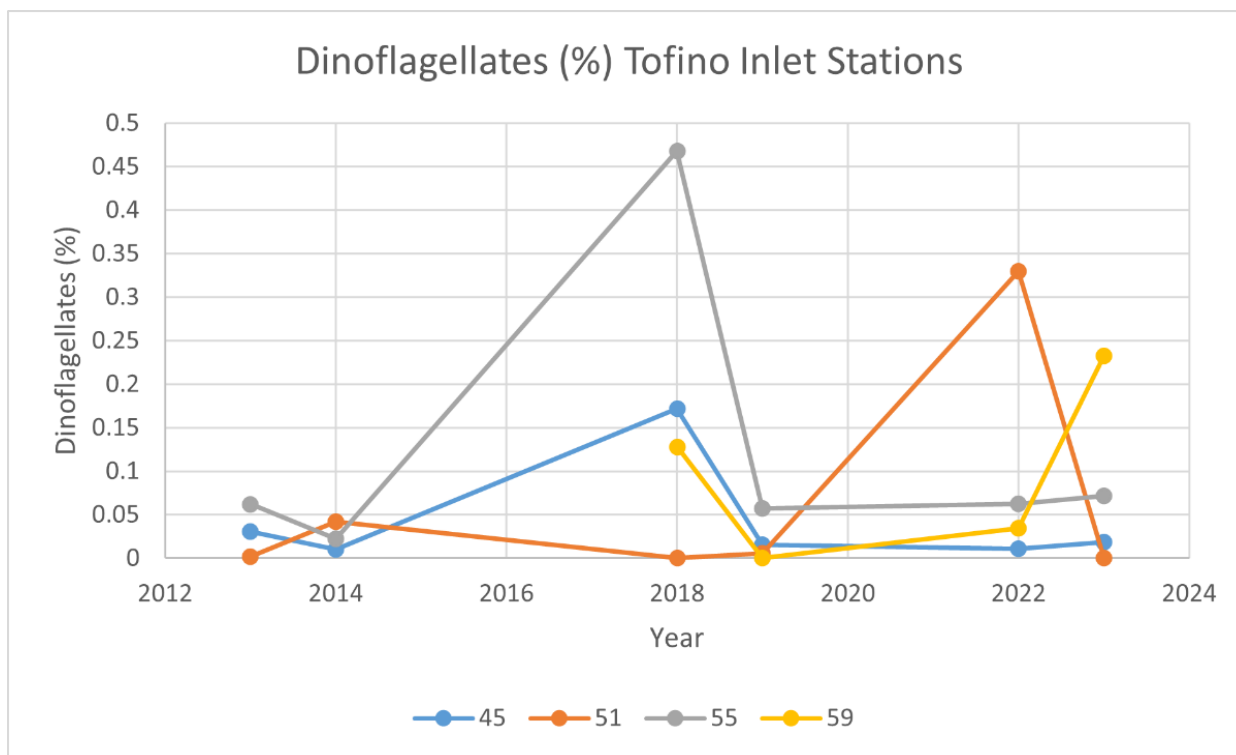


Figure 8. Percent of phytoplankton community composition made up of dinoflagellates by station per year for Tofino Inlet 2013-2023.

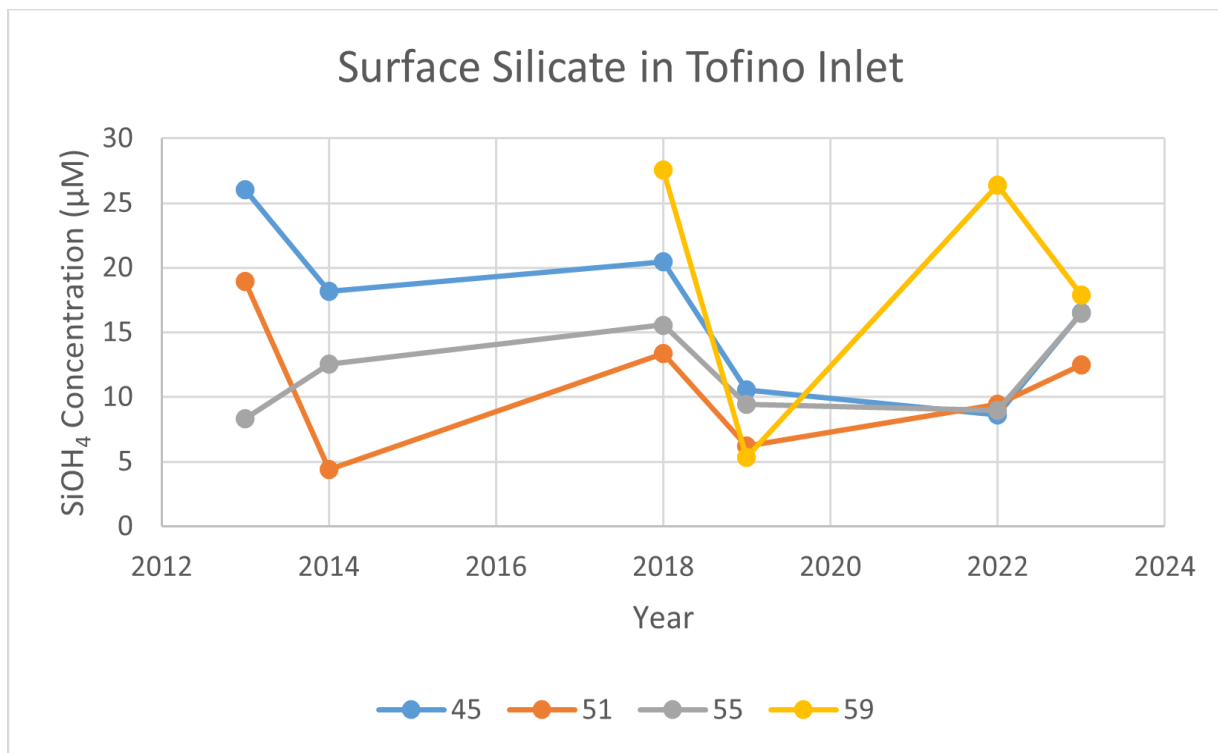


Figure 9. Surface SiOH₄ concentration in µM at stations 45, 51, 55, and 59 in Tofino Inlet 2013-2023.

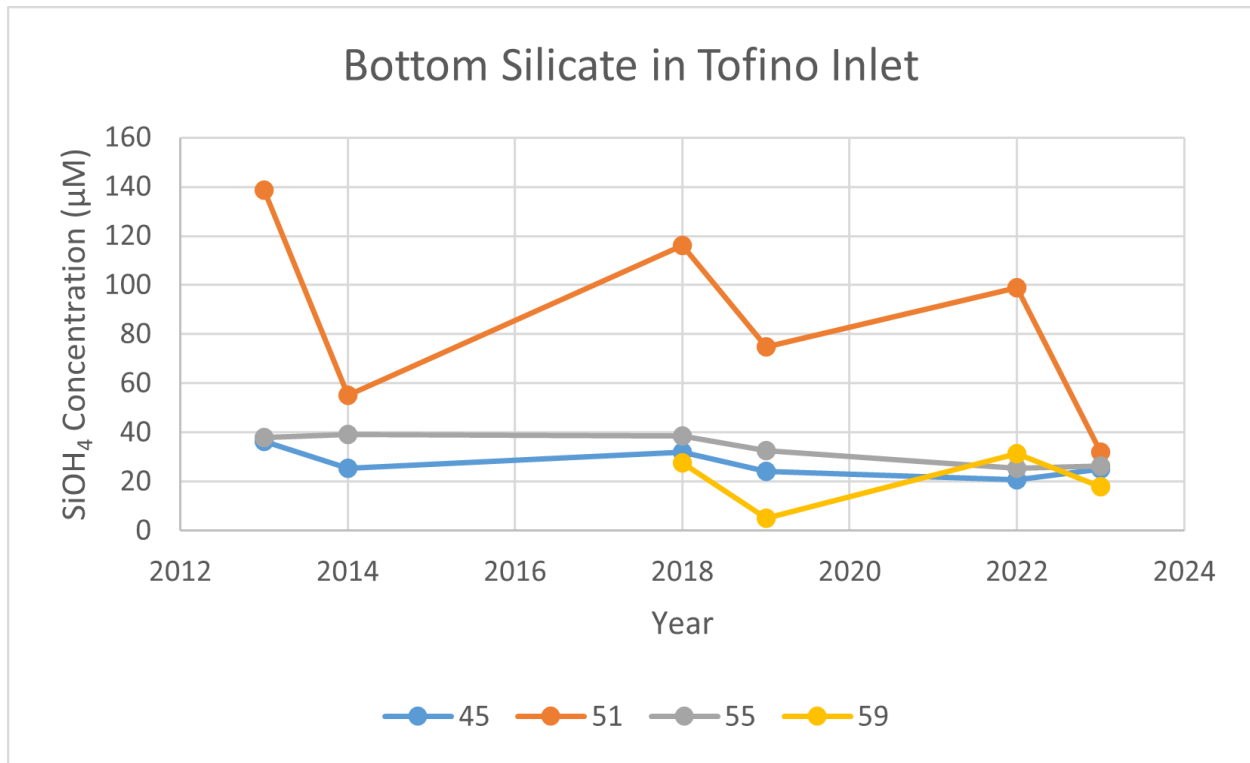


Figure 10. Bottom SiOH_4 concentration in μM at stations 45, 51, 55, and 59 in Tofino Inlet 2013-2023.

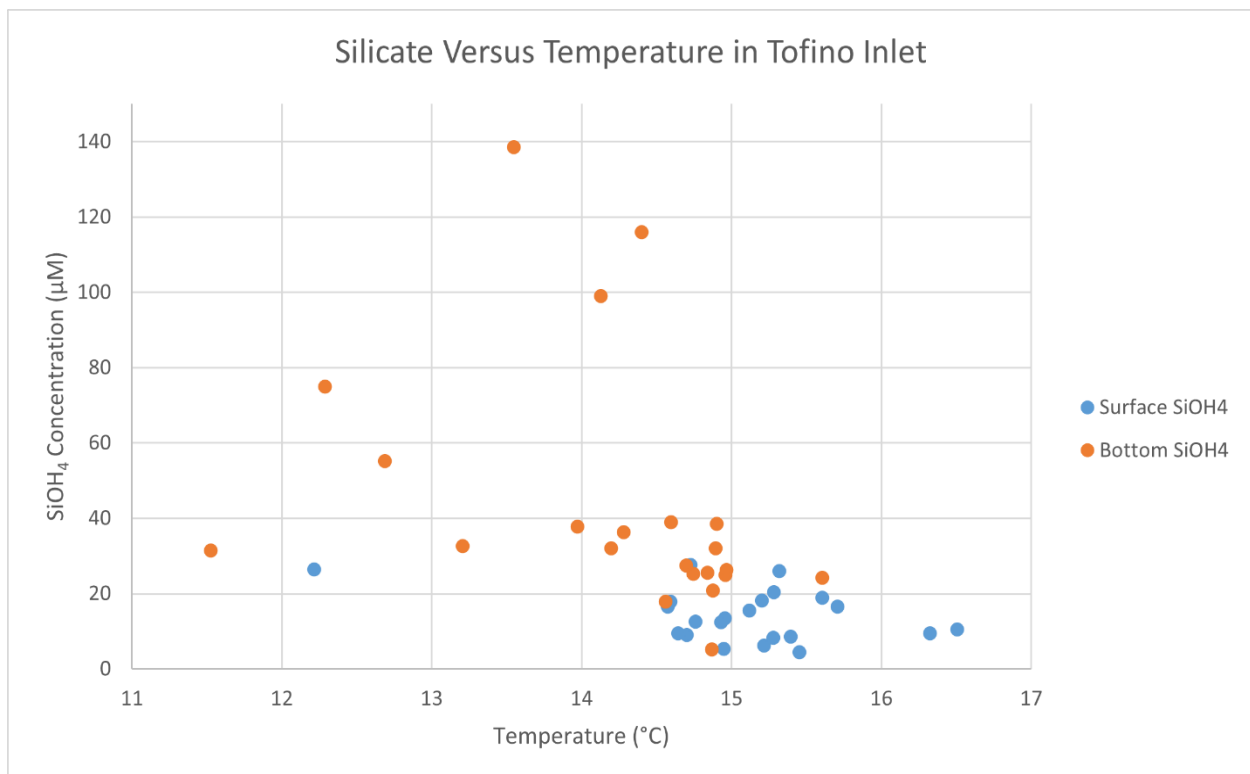


Figure 11. Silicate concentration in μM plotted against temperature in Tofino Inlet. For the surface samples this is the average of the first 10m of each stations water column, for the bottom samples, this is the bottom most temperature.

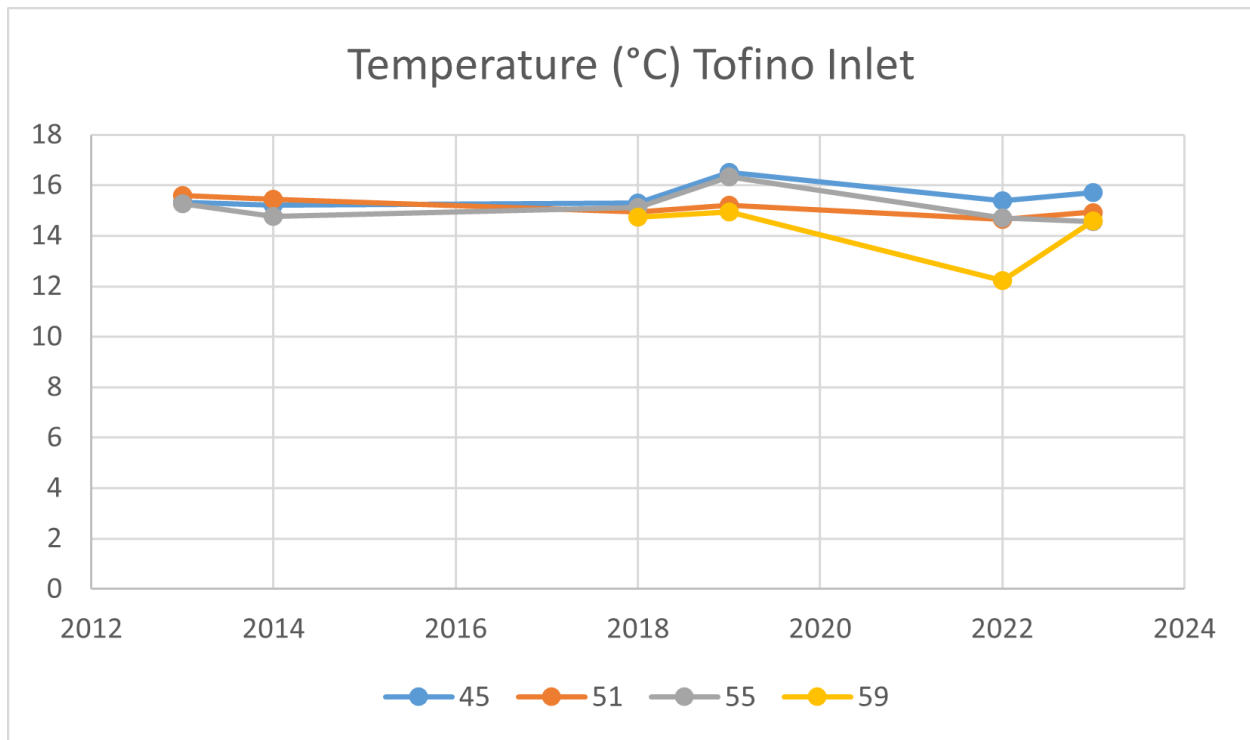


Figure 12. Average temperature (°C) of the first 10m of water at each station per year in Tofino Inlet.

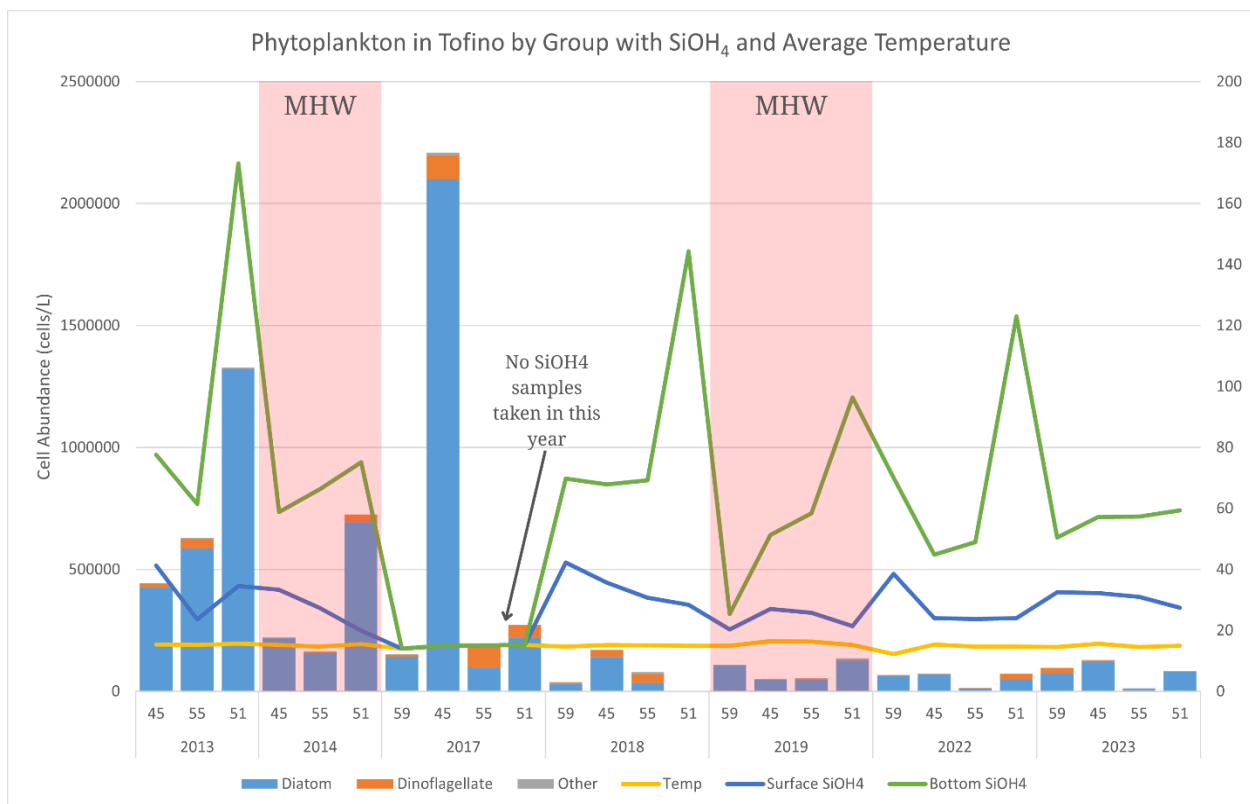


Figure 13. Graph comparing diatom, dinoflagellate, and other phytoplankton abundance with surface and bottom silicate concentrations, and average temperature in the first 10m of water at each station per year in Tofino Inlet. Marine heat wave years are denoted with red highlights.

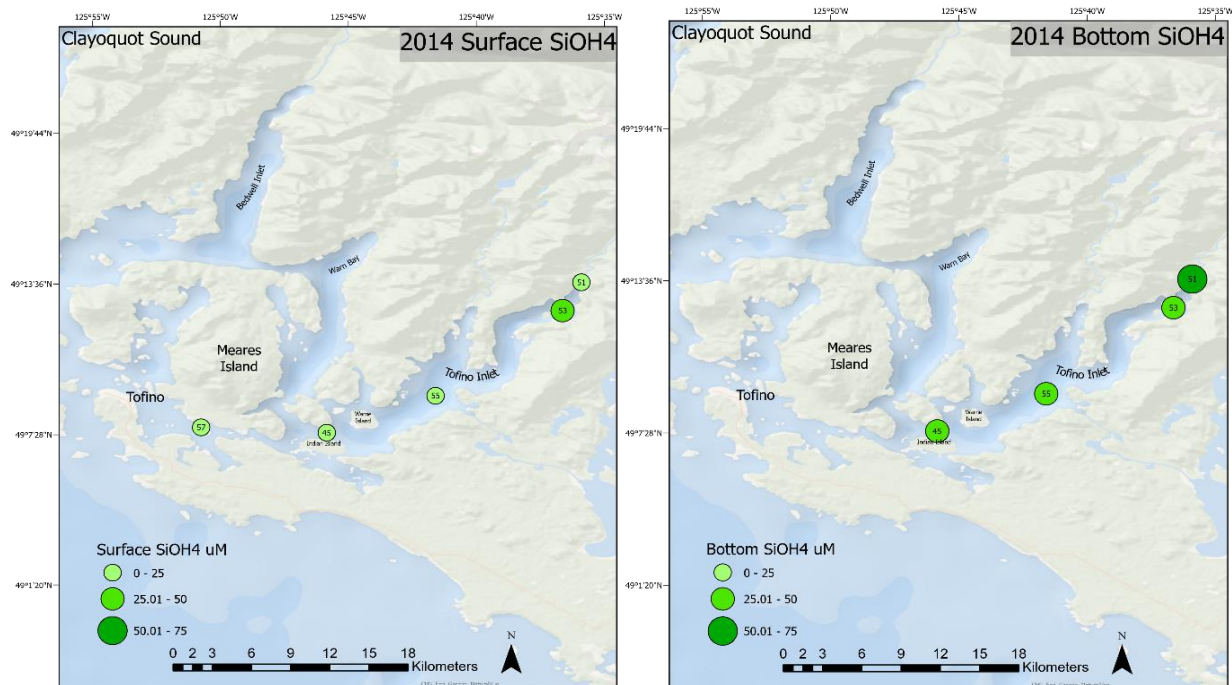


Figure 14. SiOH_4 concentrations in μM by station in 2014 in Tofino Inlet. The left graph shows surface silicate, while the right graph shows bottom silicate.

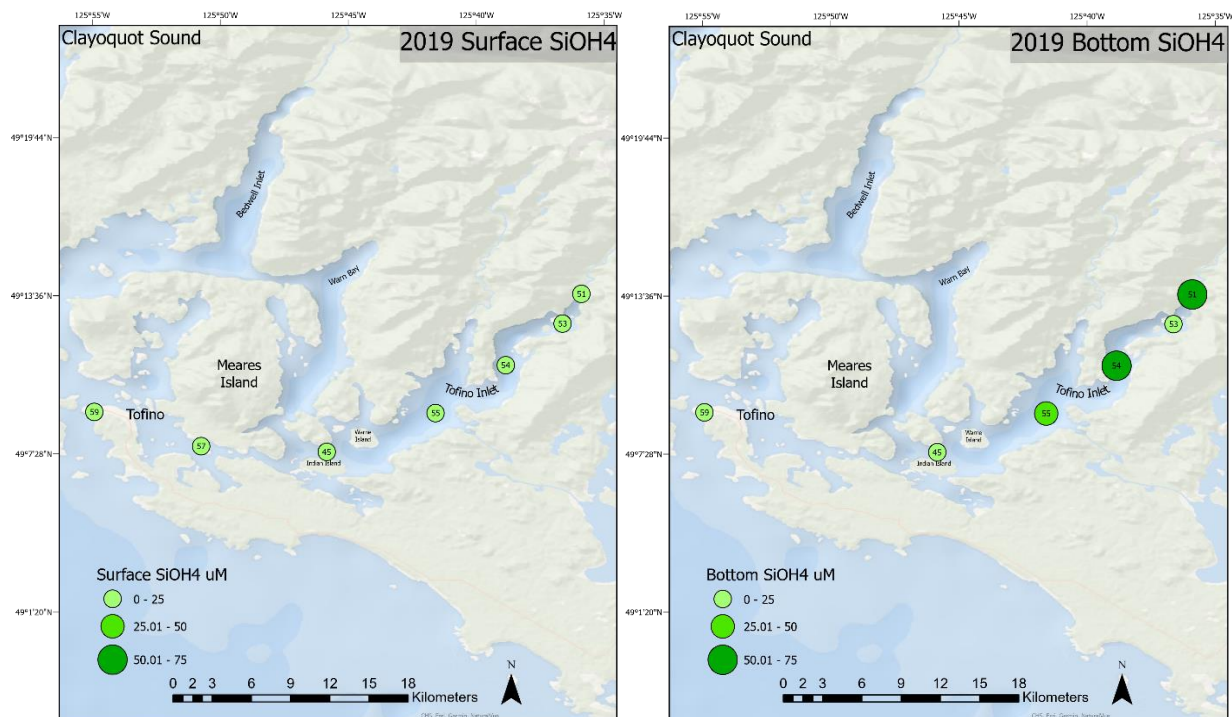


Figure 15. SiOH_4 concentrations in μM by station in 2019 in Tofino Inlet. The left graph shows surface silicate, while the right graph shows bottom silicate.

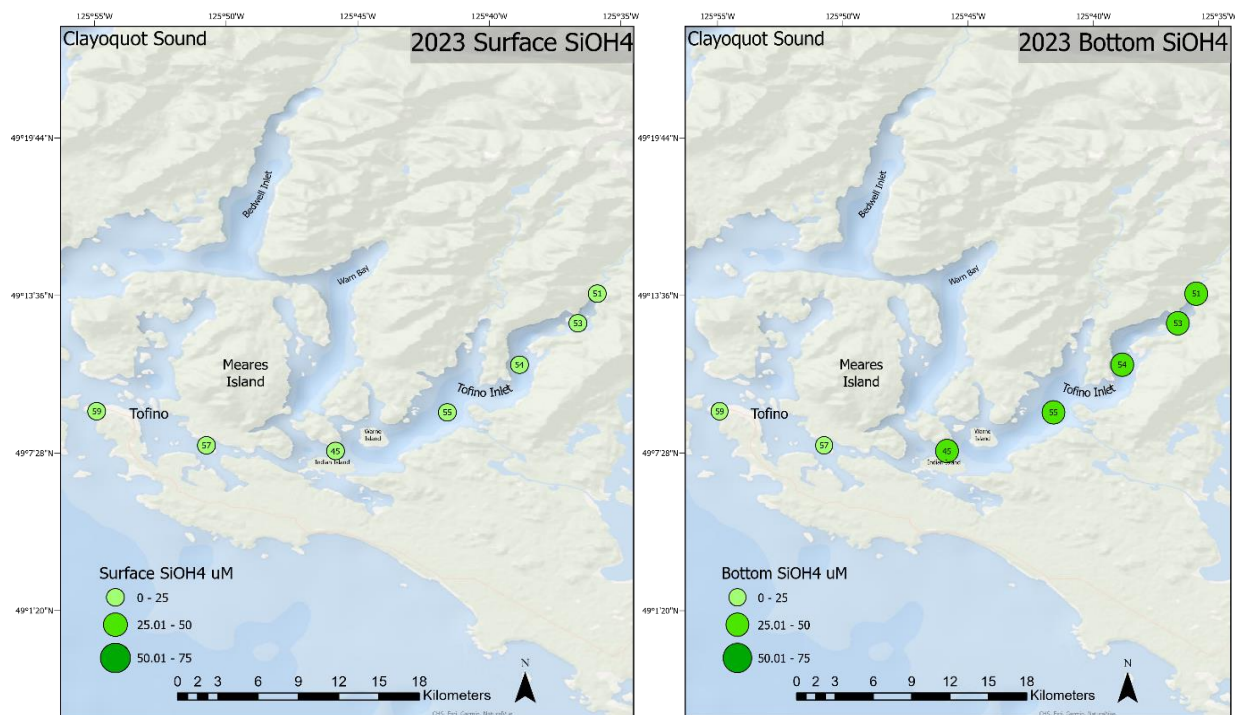


Figure 16. SiOH_4 concentrations in μM by station in 2023 in Tofino Inlet. The left graph shows surface silicate, while the right graph shows bottom silicate.

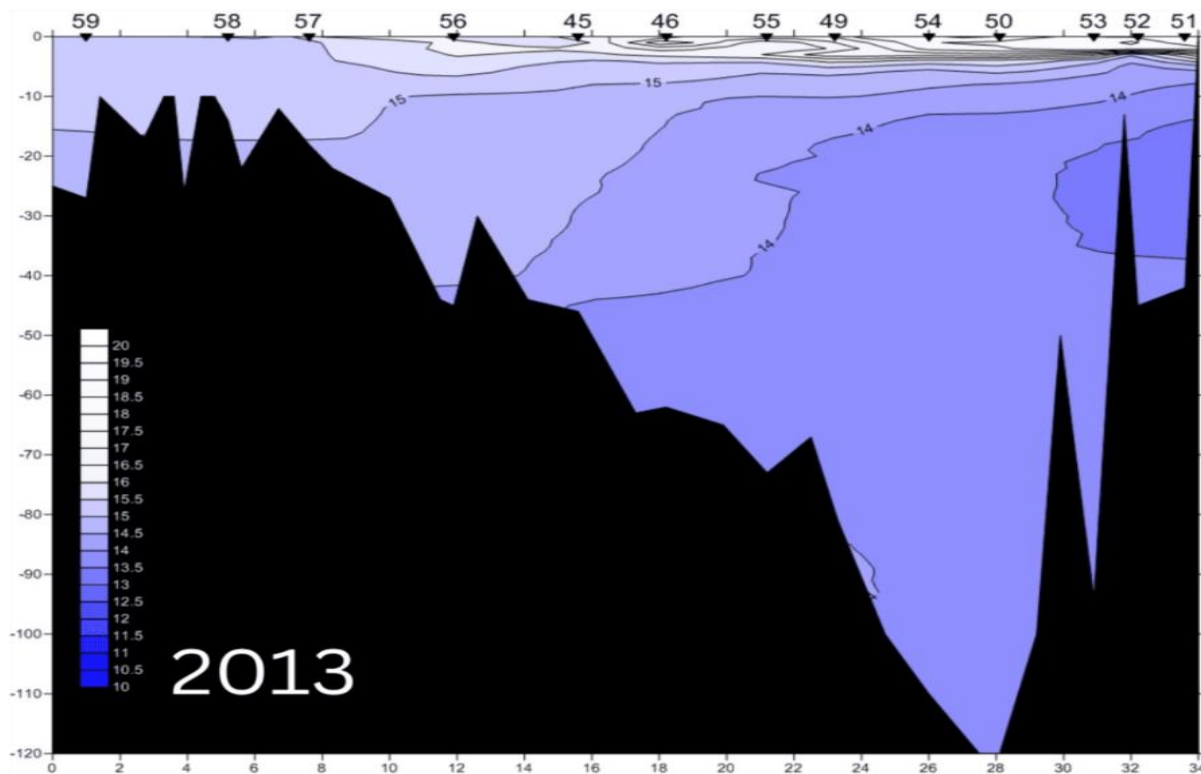


Figure 17. Longitudinal contour section of temperature ($^{\circ}\text{C}$) in Tofino Inlet in 2013.

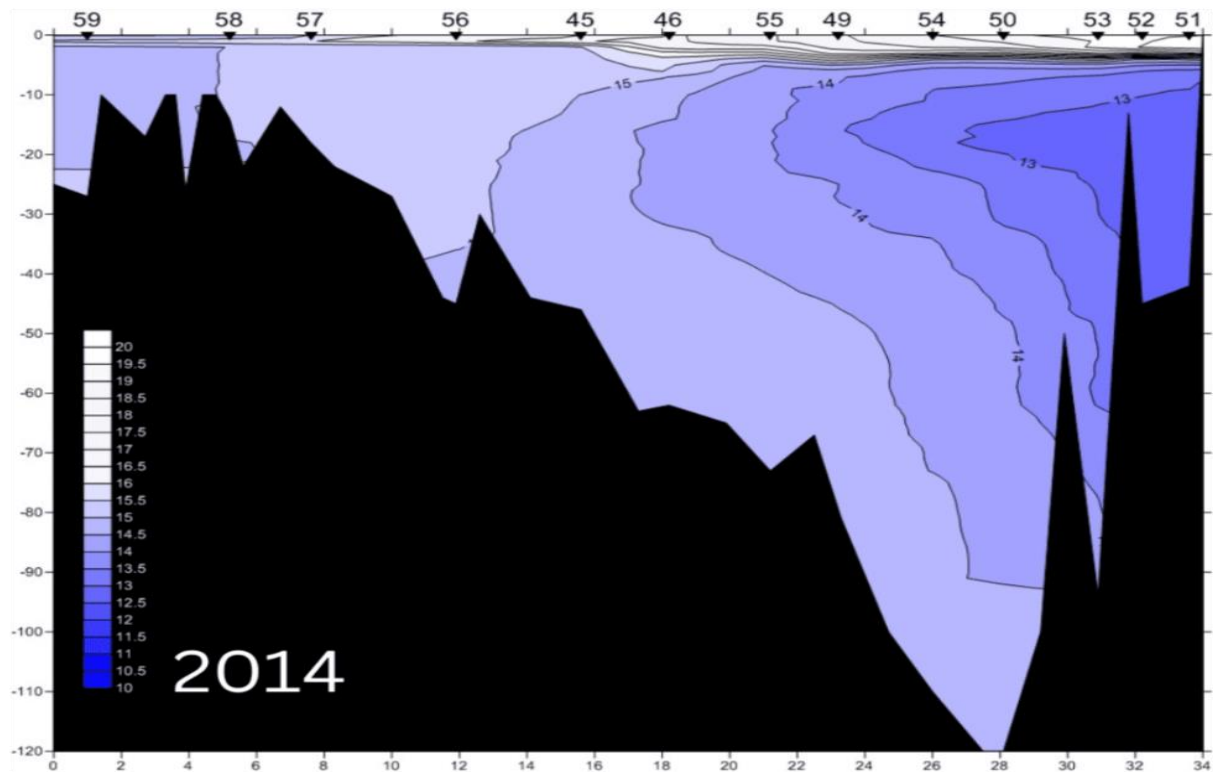


Figure 18. Longitudinal contour section of temperature (°C) in Tofino Inlet in 2014.

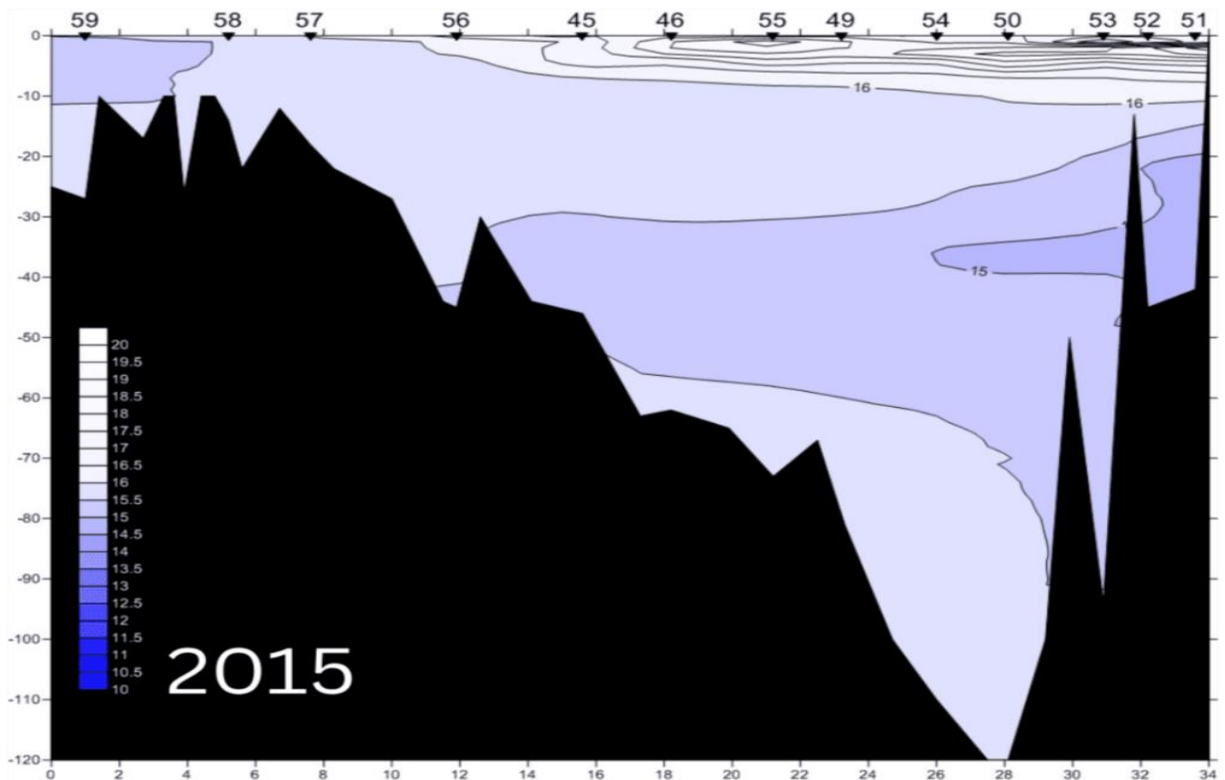


Figure 19. Longitudinal contour section of temperature (°C) in Tofino Inlet in 2015.

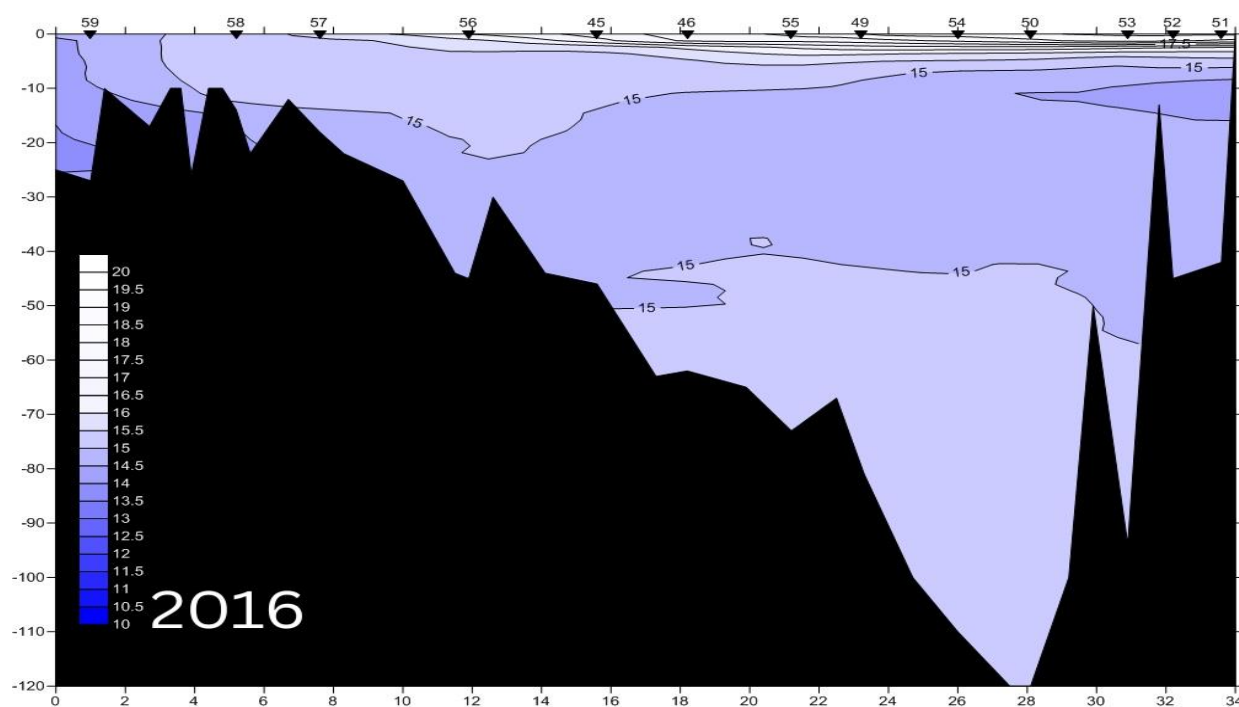


Figure 20. Longitudinal contour section of temperature (°C) in Tofino Inlet in 2016.

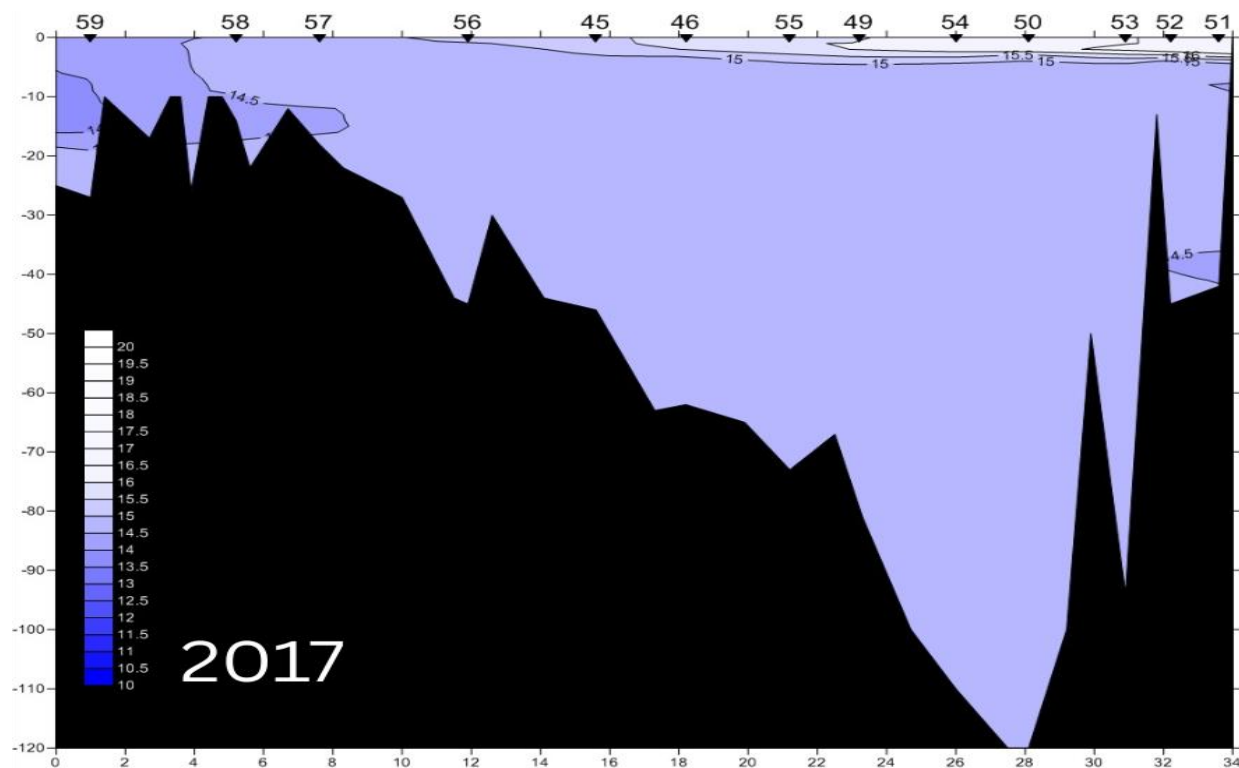


Figure 21. Longitudinal contour section of temperature (°C) in Tofino Inlet in 2017.

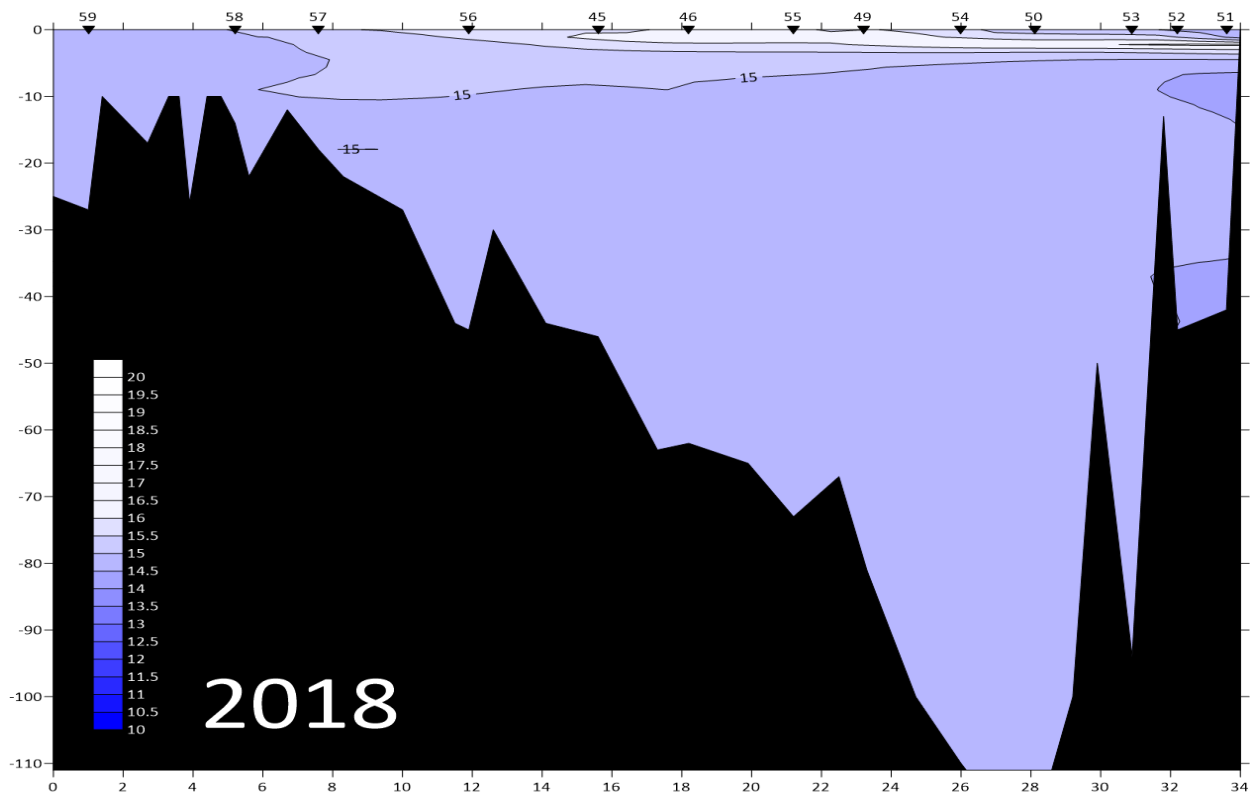


Figure 22. Longitudinal contour section of temperature (°C) in Tofino Inlet in 2018.

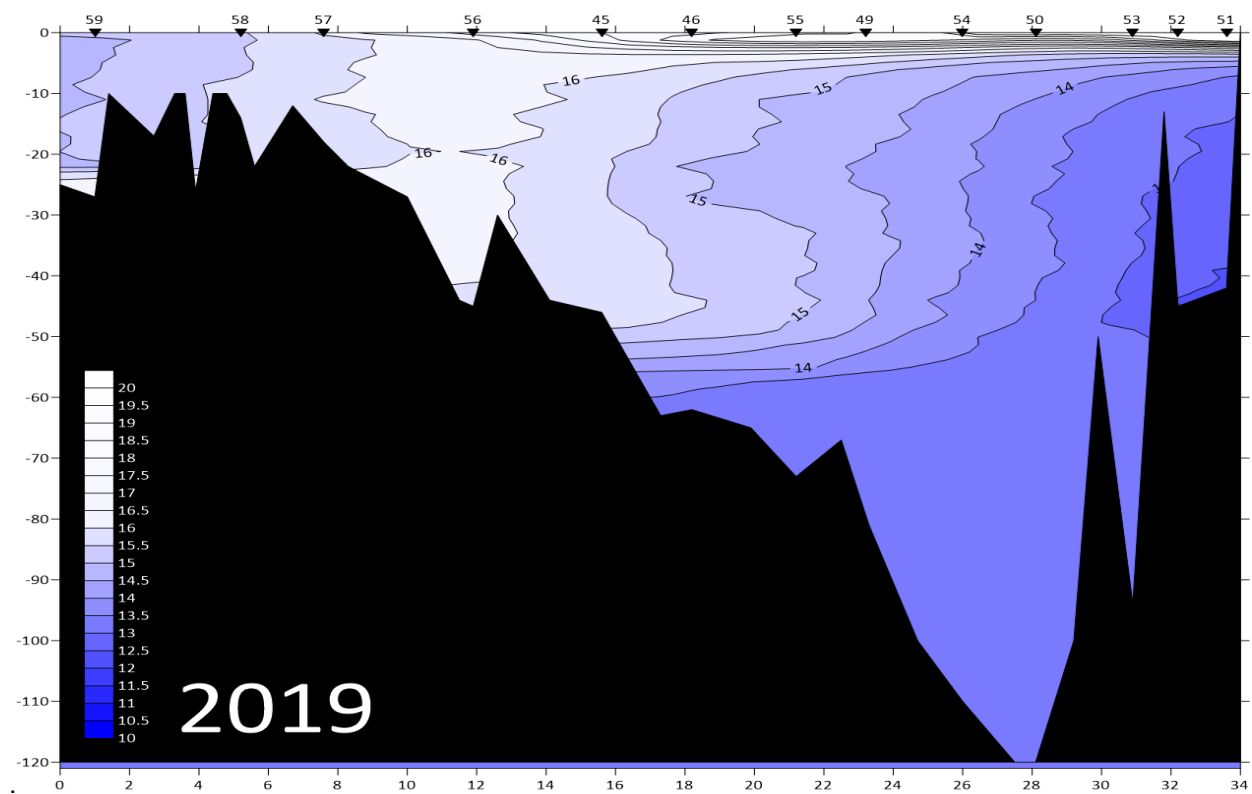


Figure 23. Longitudinal contour section of temperature (°C) in Tofino Inlet in 2019.

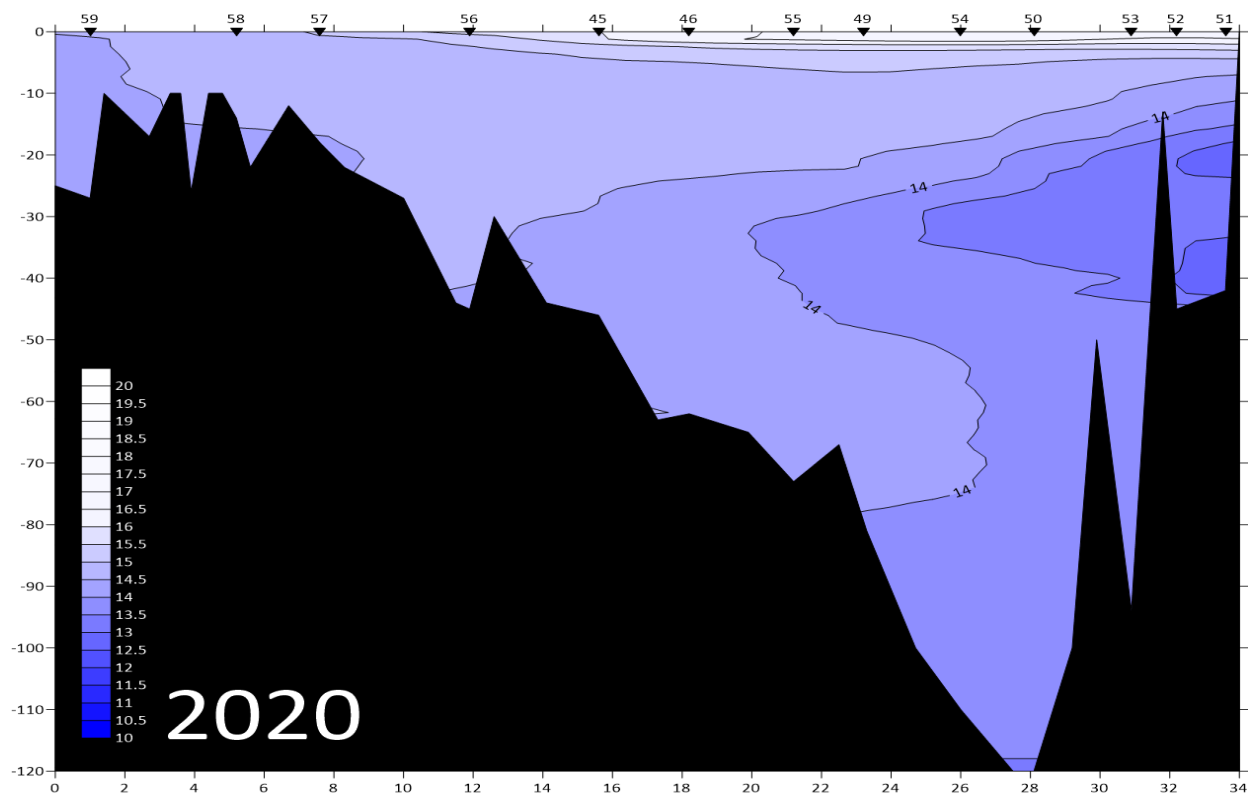


Figure 24. Longitudinal contour section of temperature (°C) in Tofino Inlet in 2020.

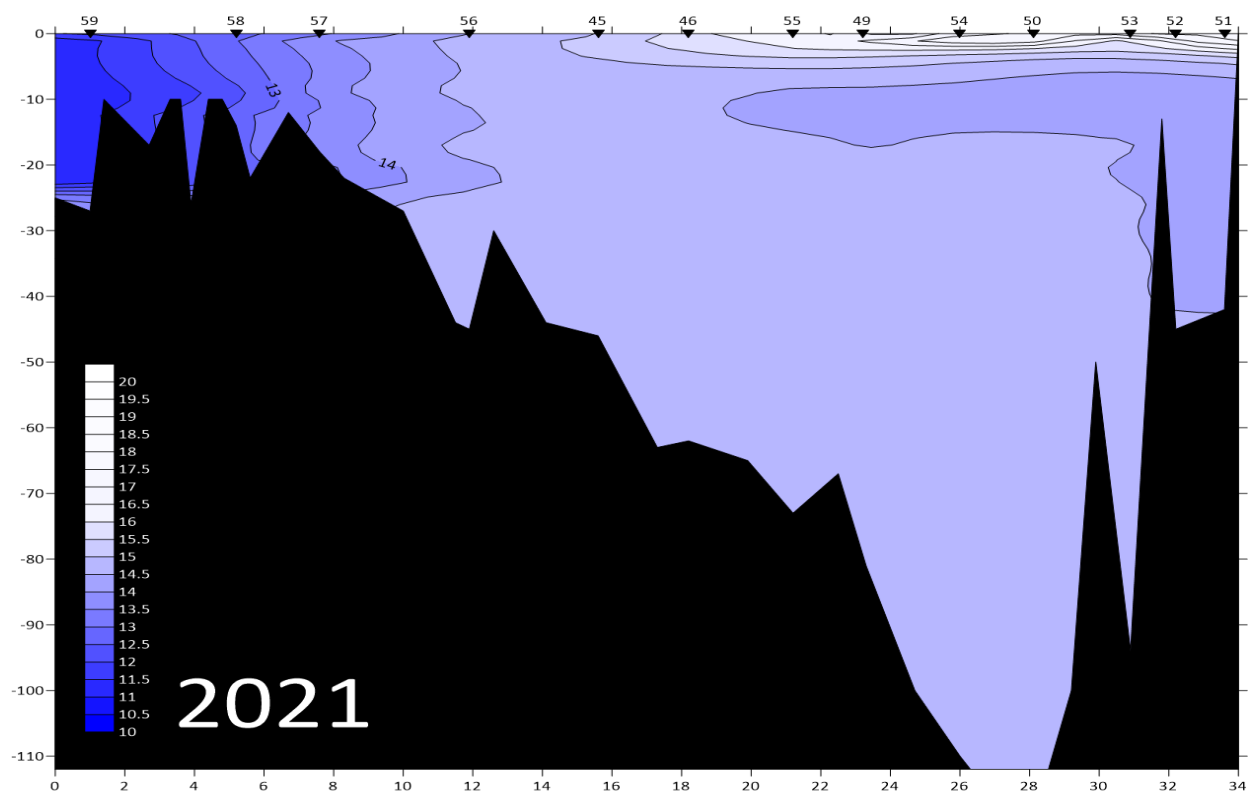


Figure 25. Longitudinal contour section of temperature (°C) in Tofino Inlet in 2021.

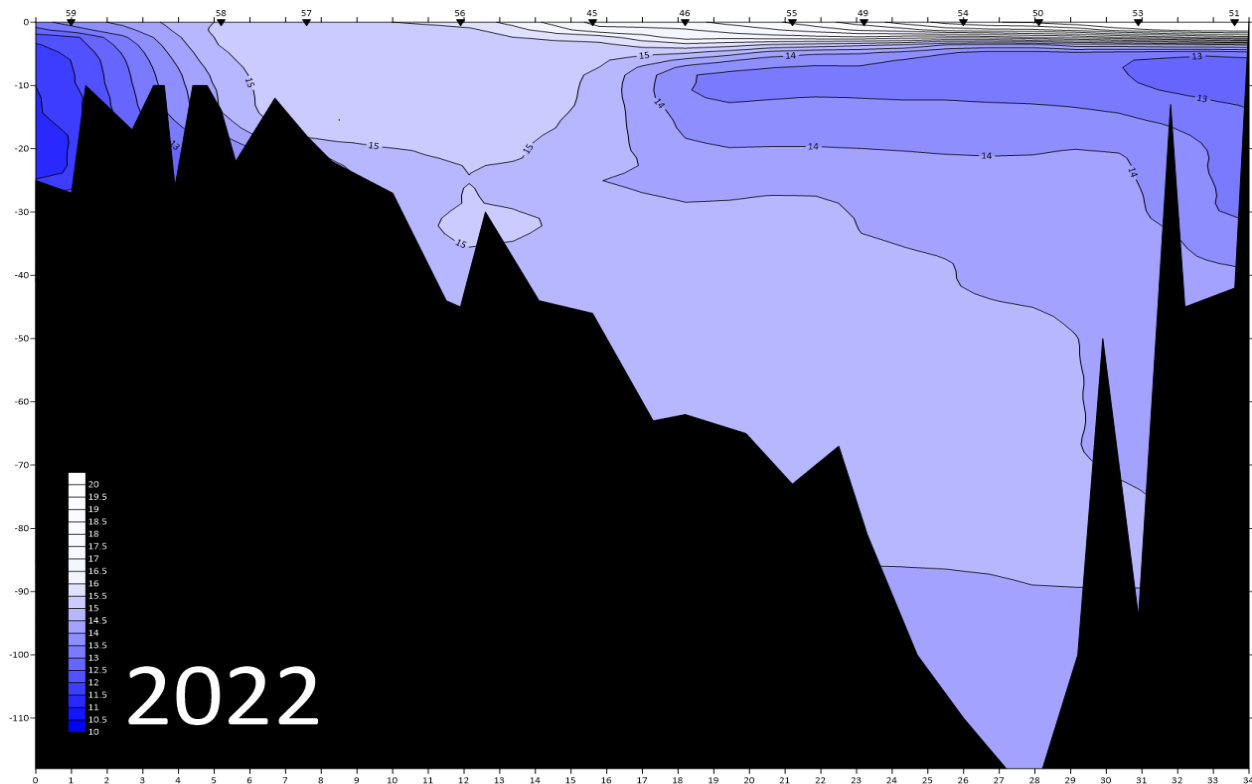


Figure 26. Longitudinal contour section of temperature (°C) in Tofino Inlet in 2022.

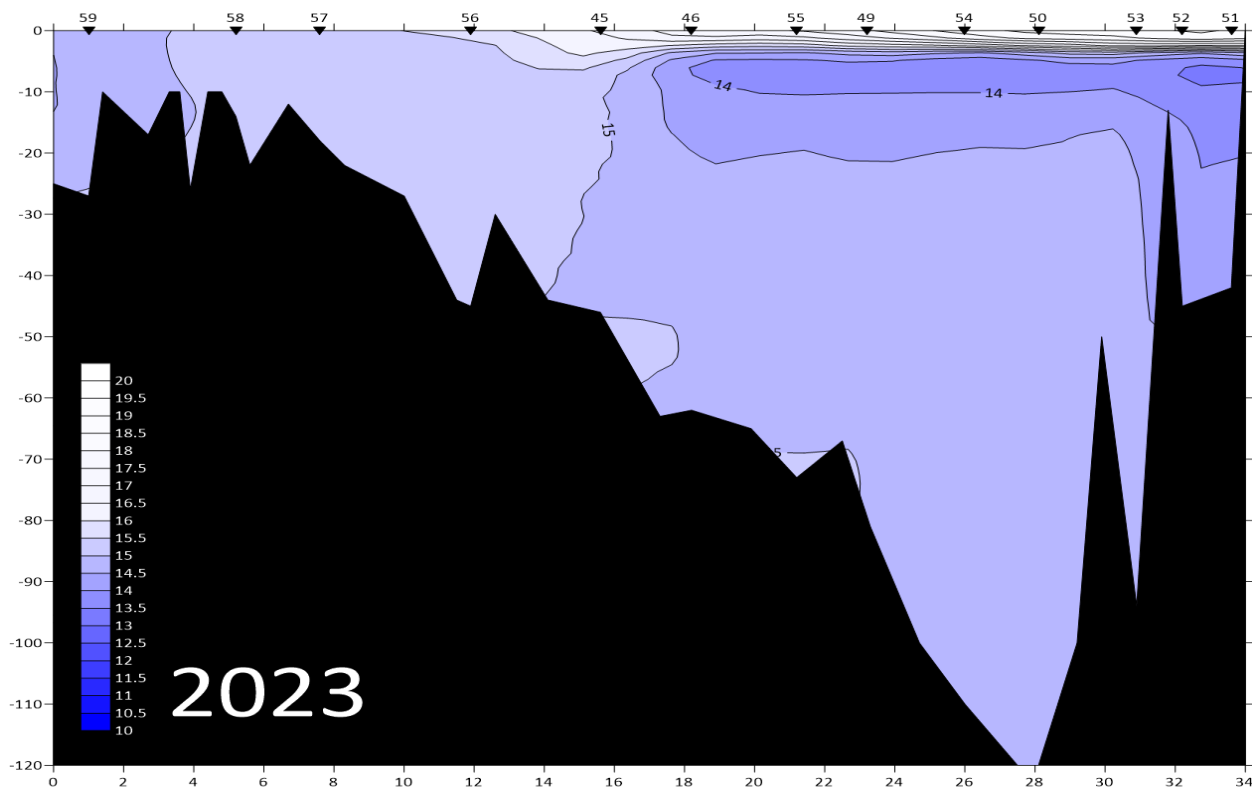


Figure 27. Longitudinal contour section of temperature (°C) in Tofino Inlet in 2023.

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