Baffin Bay Water Quality Monitoring Study: Synthesis of October 2023-December 2024 Data

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Executive Summary

The goal of this study was to quantify spatial-temporal distribution of key water quality variables in Baffin Bay and, as the length of the dataset grows, to quantify trends in these variables. Sample collection began in May 2013 from 9 sites throughout Baffin Bay and continues to present, albeit from a reduced number of sites (6) since May 2017.

In general, nitrate plus nitrite and phosphate concentrations were low in the system except for ephemeral peaks that primarily occurred in two tributaries (Cayo del Grullo, Alazan Bay) during rain events. Ammonium concentrations were variable and tended to peak during rain events, as well as during the warmer months resulting from remineralization. Dissolved organic nitrogen (DON) was consistently the largest nitrogen pool, with concentrations that routinely exceeded 40 µM and occasionally exceed 100 µM. Silicate concentrations have been variable, typically peaking following rain events but also showing drawdown during phytoplankton blooms consisting of diatoms. High chlorophyll *a* concentrations (>20 µg/l) that were reflective of dense, spatially extensive blooms of the harmful alga *Aureoumbra lagunensis* ("brown tide") occurred during low rainfall, long residence time conditions in 2013-2015, whereas episodic floods acted to reset the system by creating conditions less favorable to *A. lagunensis* (i.e., short residence time, higher inorganic nutrients). Phytoplankton blooms, consisting primarily of diatoms, were observed during or shortly after the flooding events, however. There were several instances where DON appeared to increase when chlorophyll concentrations were low but decreased during blooms, suggesting utilization of a fraction of the DON by phytoplankton to support growth.

Although chlorophyll *a* was frequently at or above state of Texas screening levels for impairment for most of the record, since approximately mid-2022 and with a few exceptions, there has been a noticeable decrease in chlorophyll *a*. The reason(s) for this recent decrease is unclear at this point but is likely complex. For example, an effort has begun in earnest over the past two years to address nutrient pollution in the Baffin Bay watershed. However, the scale of watershed restoration efforts has been relatively small to date, and most nutrient analytes have not shown a meaningful trend in Baffin Bay. Only silicate has shown a trend, and its concentration has increased steadily over the course of the study, increasing by 2-fold during that time. The increasing silicate concentration is interesting because it potentially favors diatoms over *A. lagunensis*. Earlier in the record when *A. lagunensis* blooms were prevalent, there were indications that silicate was occasionally at low and limiting levels to diatom growth, but with the increasing

concentrations, silicate limitation is becoming less likely. One other important environmental factor that has changed over time in Baffin Bay is water level, which increased at a rate of ~9 mm/year over the study period. Increasing water levels in the system may be a factor in the decreasing chlorophyll *a* levels, namely by bringing an influx of lower chlorophyll water into Baffin Bay and also possibly by decreasing the influence of sediment-derived nutrients on the water column via an increase in water depth. These findings highlight the complex dynamics that shape water quality in Baffin Bay, with clear expression of eutrophication symptoms for most of the study period that are hypothesized to be increasingly modulated by larger-scale drivers such as high-water periods and watershed nutrient reduction efforts that will be expanding in scale/coverage. Further monitoring as well as processed based studies are required to discern the magnitude/direction of water quality changes in the system as well as the overarching drivers.

Acknowledgements

First and foremost, I thank the many volunteers who dedicated their time and resources to the collection of this water quality data in Baffin Bay. This study would not have been possible without their efforts. I am also grateful to the Celanese Corporation and Coastal Conservation Association for funding. I thank partners at the Coastal Bend Bays & Estuaries Program for their ongoing support and interest. Finally, I thank the many postdoctoral researchers, technicians and students who have contributed to the data collection and analysis over the past ten years.

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Introduction

Cultural eutrophication is a major environmental threat facing coastal ecosystems worldwide (Nixon 1995; Diaz and Rosenberg 2008). Over the past 50 years, there has been a substantial increase in nutrient loading to the coastal zone, resulting in growing expression of symptoms such as harmful algal blooms and hypoxia/anoxia formation (Nixon 1995; Boesch 2002; Rabalais et al. 2009). These symptoms often have deleterious consequences for ecosystem structure and function, resulting in such visible effects as fish kills and other animal mortalities, alteration of food webs and economic losses (Diaz and Rosenberg 1995; Boesch 2002). The most recent synthesis of data from the U.S. indicates that as of 2007, at least 30% of estuaries were considered moderately to highly eutrophic, with eutrophication pressures expected to grow in 65% of estuaries over the next decade (Bricker et al. 2007).

In the past four decades, growing expression of symptoms of eutrophication such as hypoxia and dense algal (phytoplankton) blooms have been noted in Baffin Bay. Hypoxia and excessive phytoplankton growth, which are quite possibly intricately linked, are concerning because of their potential effects on ecosystem health and fisheries in estuaries. For instance, hypoxia has been linked to several large fish kills in Baffin Bay over the past 12 years (unpubl. Texas Parks & Wildlife Spills & Kills Team reports). Hypoxia formation tends to occur during warm summer-fall months, often following freshwater pulses that inject allochthonous nutrients and organic matter and induce stratification in the bays (unpubl. Texas Parks & Wildlife Spills & Kills Team reports; Wetz, unpubl. data). Co-occurrence of phytoplankton blooms and hypoxia have been noted in Baffin Bay as well (unpubl. Texas Parks & Wildlife Spills & Kills Team reports; Walker and Wetz, unpubl. data), and overall phytoplankton biomass frequently exceeds state screening levels, raising concerns about the potential role of nutrient-laden runoff (Montagna and Palmer 2012; this study). For instance, Baffin Bay has experienced prolonged, dense blooms of the brown tide organism, *Aureoumbra lagunensis*, since 1989 (Buskey et al. 1997; Buskey et al. 2001; Cira and Wetz 2019). A fish kill occurred in 2010 and coincided not only with hypoxia, but also with a dense phytoplankton bloom of the dinoflagellate *Pyrodinium bahamense* and the diatom *Thalassiothrix sp.* (unpubl. Texas Parks & Wildlife Spills & Kills Team report).

Using data obtained primarily from TCEQ quarterly sampling, Montagna and Palmer (2012) documented a long-term increase in Kjehldahl nitrogen, nitrate and phosphate in Baffin Bay. Ammonium, chlorophyll *a* and nitrate also regularly exceeded state screening levels in a number of years. While state agency sampling efforts in Baffin Bay have been valuable for documenting long-term water quality changes in the system, their limited spatial-temporal coverage hinders determination of the timing and location of symptoms of water quality degradation, and also preclude determination of the main cause(s) of water quality degradation in the system. Here results are presented from an ongoing water quality monitoring study, the goals of which are to quantify spatial-temporal distributions of key water quality variables in Baffin Bay, and to increase our understanding of the drivers of water quality change in this system.

Methods

Study location – Baffin Bay is a shallow (≤ 2-3 m depth) South Texas coastal embayment adjacent to the Laguna Madre (Figure 1). Residence time of water in Baffin Bay typically exceeds 1 year due to minimal tidal influence and freshwater inflows, although lower residence times on the order of weeks-months have been observed during high rainfall conditions (Cira and Wetz 2021), and the system is prone to hypersaline conditions due to evaporation exceeding precipitation (Shormann 1992). Circulation in Baffin Bay is primarily driven by winds.

Meteorological and water level data – Monthly mean precipitation data from the Naval Air Station Kingsville was obtained from the National Climatic Data Center. Using data from January 1973 through December 2013, monthly long-term mean precipitation was calculated. The deviation from this monthly long-term mean during the study period was then calculated and is referred to as precipitation "anomaly". Monthly mean water level data was obtained from the Texas Coastal Ocean Observation Network station 8776604, located at the mouth of Baffin Bay.

Sample collection – Water samples were collected on a monthly basis from May 2013 to present at 6 sites in Baffin Bay (Figure 2). Water samples were collected by volunteer citizen scientists from the start of the study until May 2017 and from July 2022-present. In order to qualify for this program, volunteers had to undergo rigorous training in the lab of Dr. Michael Wetz (Texas A&M University - Corpus Christi) and demonstrate competency in field sample collection (documentation retained in Wetz lab). At each site, a profile of salinity, temperature, conductivity, dissolved oxygen and pH was obtained by lowering a YSI ProPlus sonde at 0.5 m increments through the water column. Surface and near bottom discrete water samples were collected in a Van Dorn sampling device and transferred to acid-washed amber polycarbonate bottles. Bottles were stored on ice until return to a shore-based facility where processing of samples occurred.

Sample analyses – Chlorophyll *a* was determined from samples collected on, and extracted from Whatman GF/F filters (nominal pore size 0.7 µm). Chlorophyll was extracted using 90% HPLC-grade acetone and analyzed fluorometrically on a Turner Trilogy fluorometer. Inorganic nutrient concentrations were determined from the filtrate of water samples that were passed through 25 mmGF/F filters and stored frozen (−20C) until analysis. After thawing to room temperature, samples were analyzed on a Seal QuAAtro autoanalyzer. Standard curves with five different concentrations were run daily at the beginning of each run. Fresh standards were made prior to each run by diluting a primary standard with low nutrient surface seawater. Deionized water (DIW) was used as a blank, and DIW blanks were run at the beginning and end of each run, as well as after every 8–10 samples to correct for baseline shifts. For determination of DOC and TDN concentrations, water samples were collected in acid-washed amber polycarbonate bottles. Bottles were stored on ice until return to a shore-based facility where processing of samples occurred. DOC and TDN were determined using the filtrate of water samples that passed through precombusted 25 mm GF/F filters and stored frozen (−20ºC) until analysis. Samples were subsequently analyzed using the High Temperature Catalytic Oxidation method on a Shimadzu TOC-Vs analyzer with nitrogen module. Standard curves were run twice daily using a DIW blank and five concentrations of either acid potassium phthalate solution or potassium nitrate for DOC and TDN, respectively. Three to five subsamples were taken from each standard and water sample and injected in sequence. Reagent grade glucosamine was used as a laboratory check standard and inserted throughout each run, as were Certified Reference Material Program (CRMP) deep-water standards of known DOC/TDN concentration. Dissolved organic nitrogen (DON) was determined by subtracting dissolved inorganic nitrogen (ammonium, NOx) from TDN.

Results

At the beginning of the study period in spring 2013, Baffin Bay was experiencing a significant, prolonged drought (Figure 3). In early fall 2013, the drought began to lessen and precipitation patterns more in accordance with long-term monthly averages developed. By spring 2015, several periods of intense rainfall occurred in the Baffin Bay watershed. These conditions reoccurred in spring 2016. From summer 2016-spring 2018, average to below average rainfall was observed. In summer 2018, several months of above average rainfall were noted, followed by average to below average rainfall through spring 2021. With the exception of a few brief periods of heavy rainfall in May-June 2021, August 2022 and April 2023, the period from mid-2021 to present has been relatively dry.

Physical setting – Water temperature varied little between sampling locations. A distinct seasonal pattern was observed, with temperatures increasing in late winter-early spring, peaking during summer, and then decreasing in early fall (Figure 4). No clear trends in water temperature were observed. Salinity was very high at the start of the sampling period in May 2013, exceeding 70 at site 5 (upper Alazan) and site 2 (Laguna Salada) (Figure 5). Salinity tended to decrease through the middle of 2015, with the decrease accelerating in spring 2015 as a result of heavy rainfall in the watershed. From summer 2015 to summer 2016, salinity gradually increased to the mid-30's at most locations. After a brief period of above average rainfall in early-mid 2016 resulted in sharp salinity drops at sites 1 and 5, salinity resumed its increase and was ≥ 40 by October 2016. Salinity remained ≥ 40 until summer 2018, after which rainfall increased and salinities decreased in the bay to < 30 through February 2019. During spring 2019, salinity began to increase sharply and reached > 40 by September 2019. Salinity generally remained in the 30's-40's until June 2021, when a sharp decrease occurred resulting from heavy rainfall in the watershed. Salinity increased gradually thereafter, remaining < 30 until May 2022, and reaching >40 by July 2022. Salinity has exceeded 40 since then except for episodic decreases following rain events at certain sites. Strong salinity stratification (i.e., higher salinity in bottom waters than surface waters) of the water column was observed only episodically, being most pronounced at tertiary bay sites that were influenced by runoff, especially during 2015-2016, in late spring 2020, in early summer 2021, and May 2023 (Figure 6).

Biological-chemical dynamics – Chlorophyll concentrations exceeded the TCEQ screening level (11.6 µg/l) in 429 of 822 samples (52.2%). Using a slightly more relaxed National Coastal Condition Report for "poor" condition (20 µg/l; NCCR 2012), chlorophyll was in excess in 209 of 822 sample collections (25.4%). From 2013-2017, the highest chlorophyll concentrations tended to be found in spring-summer coincident with higher water temperatures, especially when *A. lagunensis* was the dominant phytoplankton taxa from 2013-early 2015 (Figures 4,7; see also Cira et al. 2021, Beecraft et al. 2023). In 2018, a noticeably different pattern emerged, with a spring bloom noted at sites 1 and 2, followed by a much larger and more widespread winter (December

2018-March 2019) diatom bloom. During the time series, prolonged episodes of high chlorophyll were observed during both dry conditions (such as 2013-2014 and early 2018 *A. lagunensis* blooms) and during wet conditions (such as late 2018-early 2019 diatom blooms, mid-2021 to mid-2022 blooms) (Figures 7,8). It is notable that the lowest chlorophyll concentrations in the time series were observed from late 2022-present. Over the course of the study, the annual mean chlorophyll *a* concentration has decreased by ~2-fold (Figure 9). From a spatial standpoint, chlorophyll concentrations tended to be highest at site 2 (17.4 ± 14.1 µg/l), followed by sites 1 and 4 (15.7 ± 13.4 µg/l and 15.0 ± 10.3, respectively), site 3 (14.5 ± 9.9 µg/l), site 5 (14.1 ± 10.7 µg/l) and site 6 (13.4 ± 10.5 µg/l) (Figure 7).

N+N concentrations were generally very low in the system. At the beginning of the study, N+N exceeded 5 µM at all sites except 1 (4.4 µM) (Figure 10). Aside from this, high (>10 µM) concentrations of N+N were only observed during wet periods, and these solely occurred at sites 1 and 5. Few obvious differences between surface and bottom N+N concentrations were observed, except during wet conditions when concentrations were occasionally higher in surface waters and during summer 2013 when N+N concentrations were occasionally higher in bottom waters (Figure 11). Ammonium concentrations exhibited a high degree of spatial-temporal variability. Higher concentrations were often observed during warmer months of the year (Figure 12). However, higher concentrations (>10 µM) were also observed during high rainfall conditions, especially (but not limited to) at the tertiary bay sites (1, 2, 5). Thus, ammonium appears to be indicative of both internal recycling (i.e., higher concentrations during warmer months) and watershed loading sources (higher concentrations during wet conditions). Higher ammonium concentrations were occasionally observed in bottom waters (Figure 13), consistent with a role for recycling in, and release from sediments. By far, the dominant form of dissolved nitrogen during the study period was dissolved organic nitrogen (DON), with DON concentrations routinely exceeding 40 µM (Figures 14,16). No clear seasonal or interannual pattern was observed in terms of DON (Figure 14), and only slight differences between surface and bottom DON concentrations were observed (Figure 15). DON peaks in both mid-late 2016 and late 2019 both corresponded with relatively low chlorophyll levels, while DON "troughs" in late 2013 to mid-2015 and early 2018 to early 2019 corresponded with higher chlorophyll levels (Figure 16), suggesting that phytoplankton may have been utilizing the fraction of the DON pool that increased in their absence or decreased in their presence. For example, at site 2 in the Laguna Salada, the DON pool decreased by ~60 ± 6%

from non-bloom to bloom periods. The C:N of the dissolved organic matter (DOM) that was utilized (5.0 ± 0.6) was lower than that of the bulk DOM pool (13.5 ± 3.0), suggesting selective utilization of DON derived from sources that produce labile organic matter (such as wastewater). Highest DON concentrations were found at site 2 (79.7 ± 16.4 µM) and site 1 (75.2 ± 13.9 µM), and were lower at sites 3-6, ranging from 66.1-70.6 µM on average.

Higher phosphate concentrations were often observed during warmer months of the year (Figure 17). However, higher concentrations (>1 µM) were also observed during high rainfall conditions, especially (but not limited to) at sites 1 and 5. Thus as with ammonium, phosphate appears to be indicative of both internal recycling (i.e., higher concentrations during warmer months) and watershed loading sources (higher concentrations during wet conditions). Higher phosphate concentrations were occasionally observed in surface waters than bottom waters during wet conditions at sites 1 and 5, and in bottom waters compared to surface waters during dry conditions (Figure 18). DIN:DIP varied from indicating nitrogen limitation (N:P<16) to indicating phosphorus limitation (N:P>16) (Figure 19), but there were no consistent temporal patterns. Out of the entire dataset, 506 of 756 samples total showed DIN:DIP<16 (66.9%) while 250 samples showed DIN:DIP>16 (33.1%).

Silicate concentrations were highly variable between sites and dates in Baffin Bay. Very low silicate concentrations were observed at various sites in 2015-2016 and late 2018-mid 2019, both of which corresponded with diatom blooms (Figure 20). Much higher concentrations were found at other times when diatom blooms were not present, most notably during the wet periods in late 2018 and in summer 2021. The DIN:Si ratio was >1, indicative of potential silicate limitation of diatom growth, in mid-2015 to mid-2016 at various sites, and again in late 2019, but has not exceeded 1 since then (data not shown). The annual mean silicate concentration increased by 2-fold over the study period (Figure 21).

Dissolved organic carbon (DOC) concentrations roughly followed the same temporal pattern as DON. No clear seasonal or interannual pattern in DOC was observed (Figure 22), and no obvious differences were observed between surface and bottom DOC concentrations (Figure 23). Highest DOC concentrations were found at site 2 (1074 ± 228 µM) and site 1 (1033 ± 219 µM), and were lower at sites 3-6, ranging from 789-910 µM on average.

Dissolved oxygen (D.O.) displayed a clear seasonal pattern that can be linked to temperature, with lowest levels being observed in the warmer months and highest levels in cooler months

(Figure 24). In summer 2013, several instances of hypoxic (<2 mg/l) bottom waters were observed. Yet in 2014, despite similarly high water temperatures, hypoxia was only observed at site 2 in July. The overall higher bottom D.O. levels in summer 2014 compared to summer 2013 may have been due to strong mixing (and less stratification; Fig. 6) in summer 2014. Hypoxia was occasionally observed at sites 1, 2 and 5 throughout the time series. Overall, the mean DO was lowest at site 2 (4.7 ± 1.7 mg/l) compared to the other sites (range from 5.2-5.5 mg/l).

Discussion

Results from this study show the presence of significant spatial-temporal variability in terms of water quality in the system. At the beginning of the study period, Baffin Bay was experiencing a prolonged drought and concurrently a major bloom of the brown tide phytoplankton species, *A. lagunensis* (Cira and Wetz 2019; Cira et al. 2021). Hypersaline conditions associated with drought have previously been shown to favor *A. lagunensis* growth in the system (e.g., Buskey et al. 1997, 2001). During the early part of this study (2013-early 2015), nutrient ratios suggested alternating conditions of nitrogen and phosphorus limitation of phytoplankton growth. However, nutrient addition bioassays conducted in 2014-2015 showed that only nitrogen addition stimulated phytoplankton growth (Wetz et al. 2017). Sun et al. (2012) found that *A. lagunensis* can use organic forms of phosphorus, and thus may be less susceptible than other phytoplankton taxa to phosphorus limitation. The strong seasonal pattern of high chlorophyll in spring-summer during 2013-early 2015, when *A. lagunensis* dominated the phytoplankton community, can be explained in part by water temperature. Field and laboratory studies have determined that water temperature may play a role in regulating the growth of *A. lagunensis* (Buskey et al. 1998; Rhudy et al. 1999; Cira and Wetz 2019). Thus, the lower levels of chlorophyll in winter could be indicative of the effects of low temperatures. Another possibility, not mutually exclusive with the temperature hypothesis, is that lower temperatures in winter reduced the availability of recycled nutrients that would otherwise support *A. lagunensis* growth. Additional field and experimental studies may be needed to further our understanding of seasonal controls on *A. lagunensis*.

From early fall 2013 through spring 2015, precipitation patterns developed that were more in accordance with long-term monthly averages, and salinities decreased. Despite the lower salinity levels, very high chlorophyll levels were noted in spring-summer 2014 as in spring-summer 2013. In spring 2015, chlorophyll noticeably decreased concurrent with several heavy precipitation events and lower salinity conditions, as did abundances of *A. lagunensis* (Cira and Wetz 2019). This was despite higher inorganic nutrient concentrations than during the earlier timeframe. There are several possible explanations for the decrease in chlorophyll. First, there was significant flushing that accompanied the spring 2015 rains in Baffin Bay, as well as introduction of inorganic nutrients, which Cira et al. (2021) suggest may have led to the demise of the brown tide bloom and favoring of diatoms instead. Another explanation (not mutually exclusive) is that microzooplankton grazing (e.g., Buskey et al. 1997, 2001) and/or benthic filter feeder removal of phytoplankton may have been depressed during the hypersaline conditions but became important again with lower salinities.

Chlorophyll remained relatively low for an extended period after the 2015 wet period, except at site 2 where a bloom of *A. lagunensis* redeveloped by summer 2015 and continued through early 2016 (Cira and Wetz 2019; Cira et al. 2021). *A. lagunensis* abundances stayed low elsewhere but were quantifiable at site 2 through early 2018 when another bloom developed (Wetz, unpubl. data). The persistence of *A. lagunensis* at site 2, along with other features of that site include long residence time, extreme hypersalinity, very high organic nutrient concentrations, and shallowness that may amplify benthic-pelagic exchange of nutrients, strongly point to the site as being an incubator for *A. lagunensis* in Baffin Bay (Barraza 2024).

Heavy rain that occurred in mid-2018 resulted in the dissipation of the *A. lagunensis* bloom at site 2, again pointing to flushing as being a contributing factor. However, chlorophyll increased in at the same time, with a diatom bloom developing throughout the bay. A similar phenomenon was observed during/after the heavy rains that occurred in May-June 2021. The blooming of diatoms during wet periods is consistent with their preference for high/pulsed inorganic nutrient inputs (Cloern and Dufford 2005; Dorado et al. 2015; Chin et al. 2022). Using a 90th percentile threshold of chlorophyll *a* concentration to classify blooms, Beecraft and Wetz (2022) estimated that 24% of high salinity (drought) observations had bloom-level chlorophyll (>33.8 µg/l) and 12% of low salinity (flood) observations were bloom-level. These findings show that Baffin Bay can experience phytoplankton blooms under both low and high inflow conditions, an artifact of the availability of nutrients and ability of the phytoplankton community composition to shift in response to the salinity, nutrient and flushing extremes that exemplify Baffin Bay.

An important goal of researchers working on Baffin Bay-related water quality issues is to identify which nutrients are fueling blooms in Baffin Bay, and sources of those nutrients. During the study period, surface N+N and ammonium levels were generally low except during wet periods, when high concentrations were commonly observed at the tributary sites. Similarly, high phosphate concentrations were observed during these periods at sites 1 and 5. These findings suggest a contribution of watershed and/or atmospheric sources to the nutrient pools. Analysis of historical TCEQ water quality data suggests that concentrations of these nutrients in watershed streams, especially San Fernando Creek (upstream of site 1) are particularly high (Wetz, unpubl. data). Output from a SPARROW nutrient loading model indicated that fertilizers and atmospheric deposition are the dominant sources of watershed-derived nitrogen to Baffin Bay, while fertilizer was the dominant source of phosphorus (Rebich et al. 2011). However, more recent source tracking work has shown that sewage is an important contributor to inorganic nitrogen pools in watershed streams, whereas a mix of sources contribute to organic nitrogen pools (Wetz et al. 2023). Elevated concentrations of ammonium and phosphate were also occasionally observed during summer in bottom waters, consistent with studies from this and other systems showing release of nutrients from suboxic sediments under warm conditions (e.g., An and Gardner 2002; Murgulet et al. 2024). These internal nutrients are likely important for *A. lagunensis* growth.

Another important nitrogen pool is DON. There were several instances between 2013-2021 where DON appeared to increase when chlorophyll concentrations were low but decreased during blooms, suggesting utilization of a fraction of the DON by phytoplankton to support growth. For example, at site 2 in the Laguna Salada, the DON pool decreased by ~60 ± 6% from non-bloom to bloom periods. It is unclear why this pattern fell apart after 2021. One possibility is a shift in the phytoplankton community that affected nutrient utilization, namely that there have been no significant *A. lagunensis* blooms since 2018 in the system. The increasing silicate concentrations may be promoting a shift towards a diatom-dominated community, and diatoms are less likely to display significant utilization of DON compared to *A. lagunensis* (Glibert 2016). The cause of the increasing silicate concentrations is unclear at this point. Silicate is largely tied to weathering products in the watershed that are delivered to the estuary via rivers, but it can also be tied to remineralization (of e.g., diatom frustules) within the estuary (Conley and Malone 1992; Frings et al. 2016). Here we did observe spikes in silicate that coincided with decreases in salinity accompanying runoff events. One possible cause for the increasing silicate is that, because of the long residence time of the estuary in general, silicate from runoff events is largely retained in the estuary and has thus accumulated over the past ~11 years. Another possibility is that land clearing around the watershed is leading to increased delivery of silicate during rain events. Regardless of the cause, additional attention on silicate availability is warranted, especially for understanding drivers of *A. lagunensis* blooms vs. diatom blooms.

DON concentrations did not display an obvious seasonal pattern, and highest concentrations tended to be in the tributaries, decreasing towards the mouth. No large-scale differences were observed between surface and bottom DON or DOC concentrations, suggesting that sediment-derived sources are less pronounced compared to the inorganic nutrient pools. These findings point to the watershed as a possible source of DON, or alternatively may indicate that inorganic nitrogen forms transported to the bay are rapidly transformed into organic nitrogen. As with DON, DOC concentrations tended to be much higher in the tributaries of Baffin Bay, possibly indicating sources such as watershed streams and/or internal sources such as phytoplankton exudation.

DOC, algal biomass and other uncharacterized organic matter sources are important because they may fuel microbial respiration and biological oxygen demand. Near bottom oxygen levels showed a distinct seasonal cycle that is undoubtedly temperature related, with lower temperatures capable of holding more oxygen than higher temperatures. Nonetheless, we occasionally observed hypoxic (<2 mg/) conditions, and oxygen levels and were generally <4 mg/l throughout summer, indicative of intensive microbial respiration and utilization of labile organic matter. Previous studies have shown that hypoxic dissolved oxygen levels, and in some cases oxygen levels of <3-5 mg/l, can have sublethal and/or lethal effects on benthic organisms (e.g., Ritter and Montagna 1999; Diaz and Rosenberg 2008).

Overall, Baffin Bay displays symptoms of eutrophication including very high organic carbon, organic nitrogen and chlorophyll concentrations, episodic hypoxia as well as symptoms not quantified here such as fish kills. Additionally, the total dissolved nitrogen (i.e., DON + ammonium, N+N) and DON concentrations observed in Baffin Bay are consistently higher than many other estuaries in the Gulf of Mexico (e.g., Bianchi 2007; Mooney & McClelland 2012; Wetz et al. 2017), which further emphasizes the degree to which Baffin Bay has been enriched with nutrients. Given the strong linkage between total nitrogen and chlorophyll along the Texas coast (e.g., Wetz et al. 2017), as well as the stimulatory effects of nitrogen on Baffin Bay phytoplankton growth in bioassays, it is reasonable to conclude that nitrogen is an important driver of eutrophic conditions in Baffin Bay and needs to be a focus of targeted reductions.

A period of decreasing chlorophyll a, particularly from mid-2022 to present, merits additional discussion. During this period, the lowest chlorophyll levels of the entire record were frequently observed. The reason(s) for this recent decrease is unclear at this point but is likely complex. Although efforts are now underway to address nutrient pollution in the Baffin Bay watershed, the scale of watershed restoration efforts has been relatively small to date. An important environmental factor that has changed over time in Baffin Bay is water level, which increased at a rate of ~9 mm/year over the study period (Fig. 25). Increasing water levels in the system may be a factor in the decreasing chlorophyll *a* levels, namely by bringing an influx of lower chlorophyll water into Baffin Bay and also possibly by decreasing the influence of sediment-derived nutrients on the water column via an increase in water depth. These findings highlight the complex dynamics that shape water quality in Baffin Bay, with clear expression of eutrophication symptoms for most of the study period that are hypothesized to be increasingly modulated by larger-scale drivers such as high-water periods and watershed nutrient reduction efforts that will be expanding in scale/coverage. Further monitoring as well as processed based studies are required to discern the magnitude/direction of water quality changes in the system as well as the overarching drivers.

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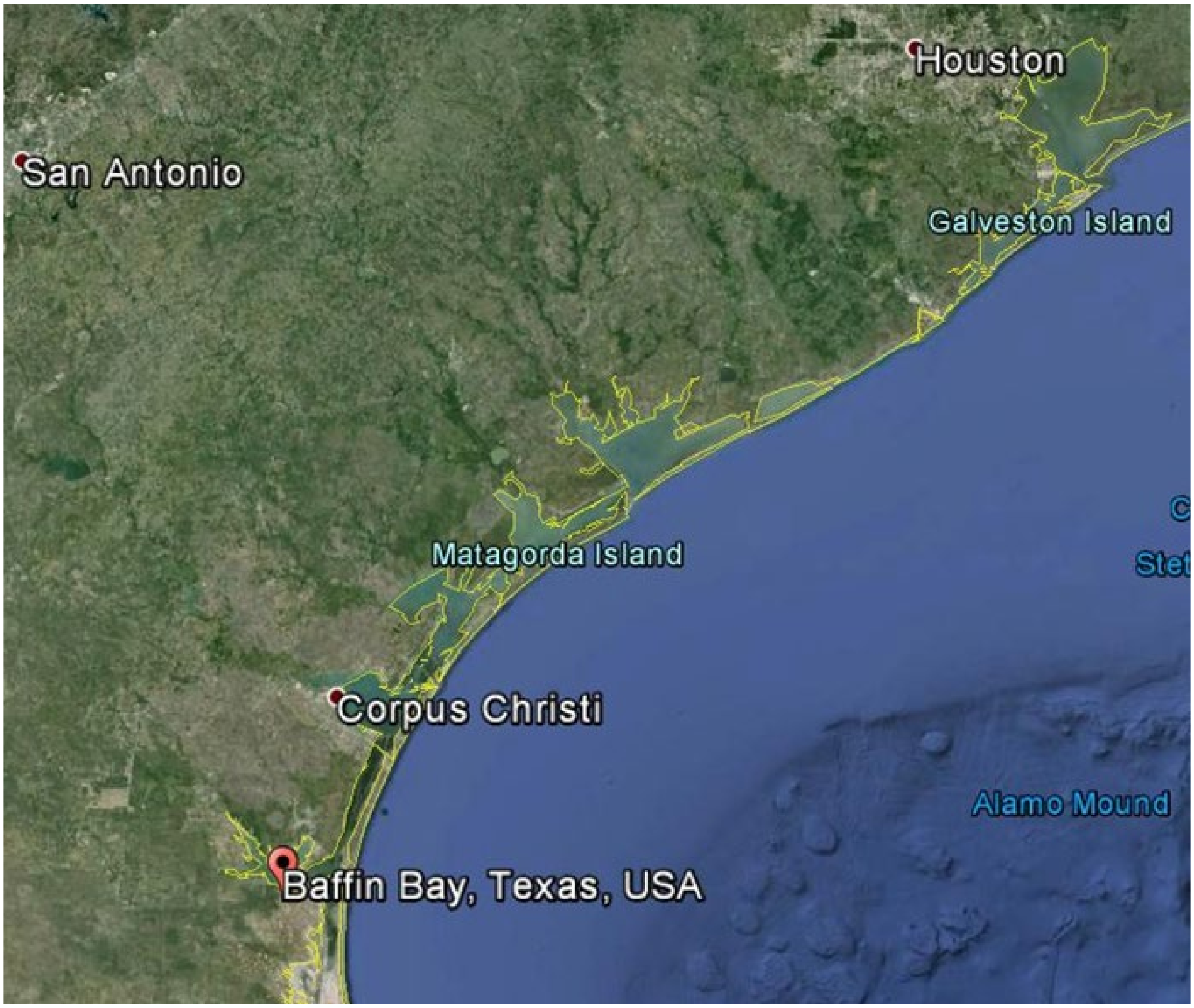

Figure 1. Map of Baffin Bay, located ~50 km south of Corpus Christi, TX.

Figure 2. Map of sampling locations in Baffin Bay. Red markers indicate two sites that are visited as part of TCEQ's quarterly monitoring program.

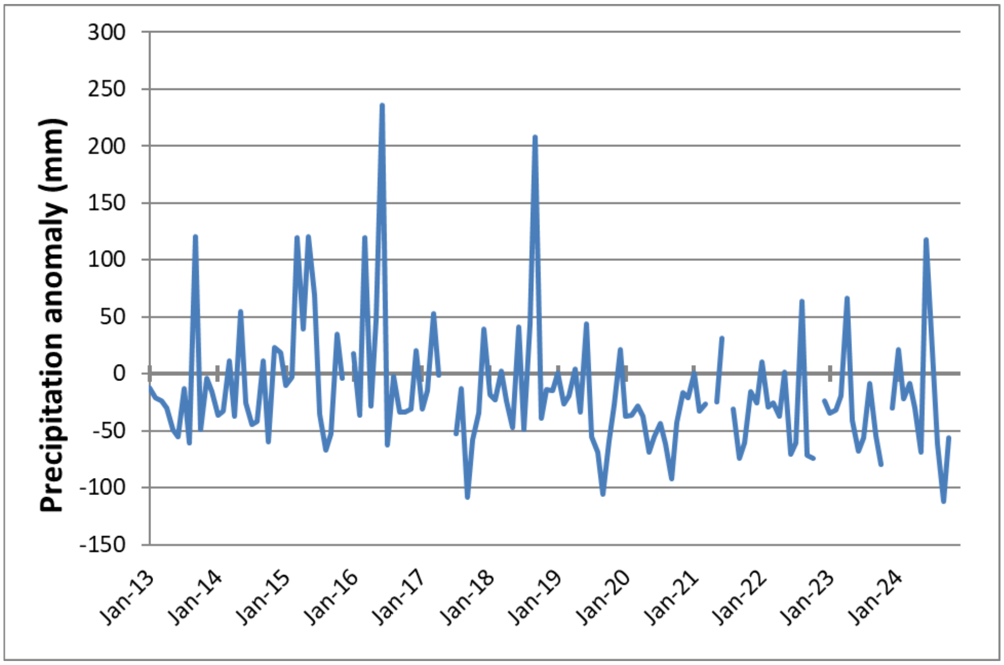

Figure 3. Precipitation anomaly for Baffin Bay.

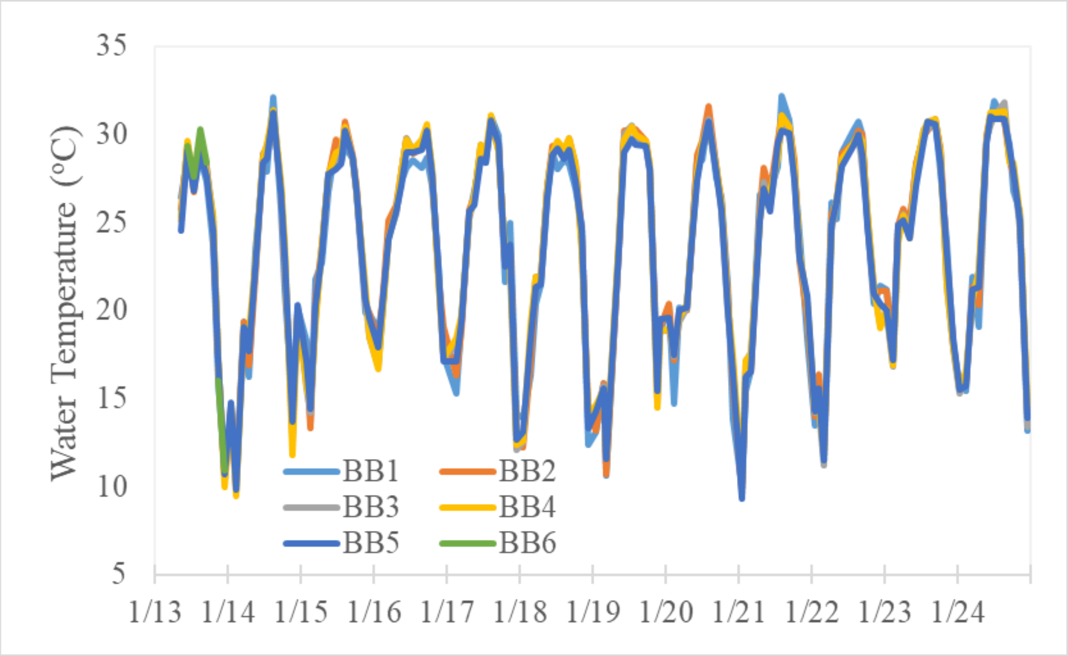

Figure 4. Surface water temperature in Baffin Bay.

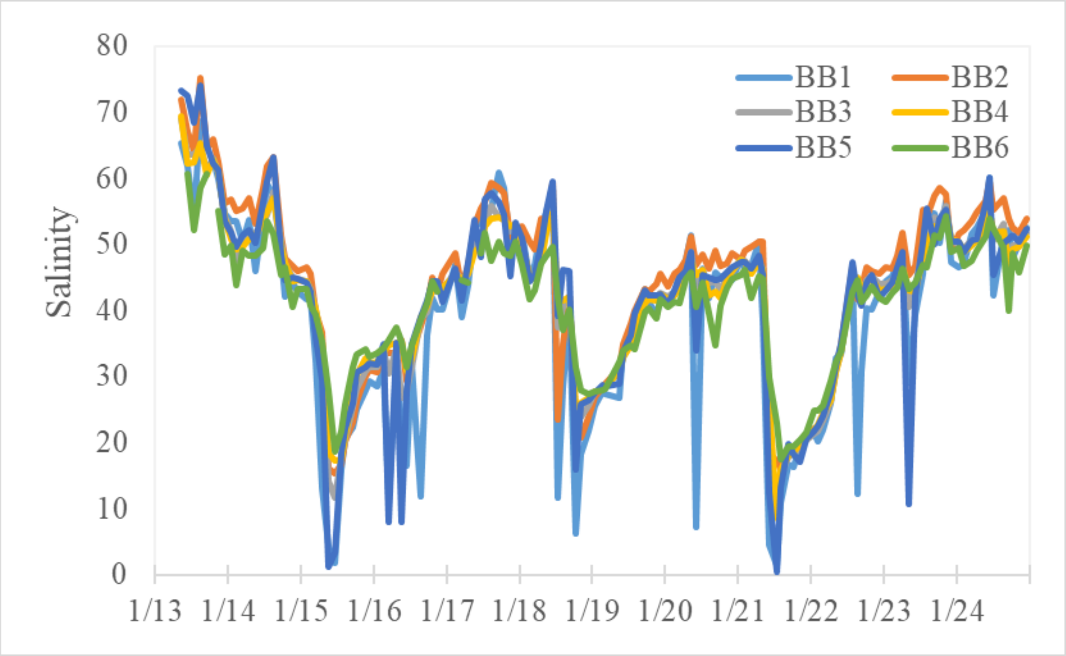

Figure 5. Surface salinity in Baffin Bay.

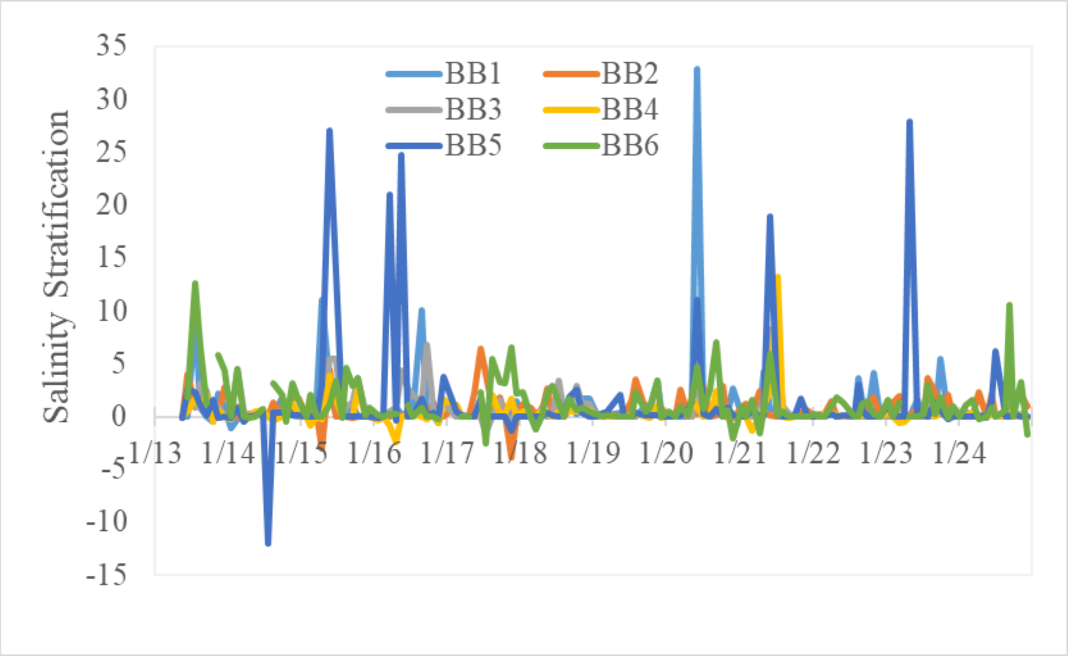

Figure 6. Salinity stratification in Baffin Bay.

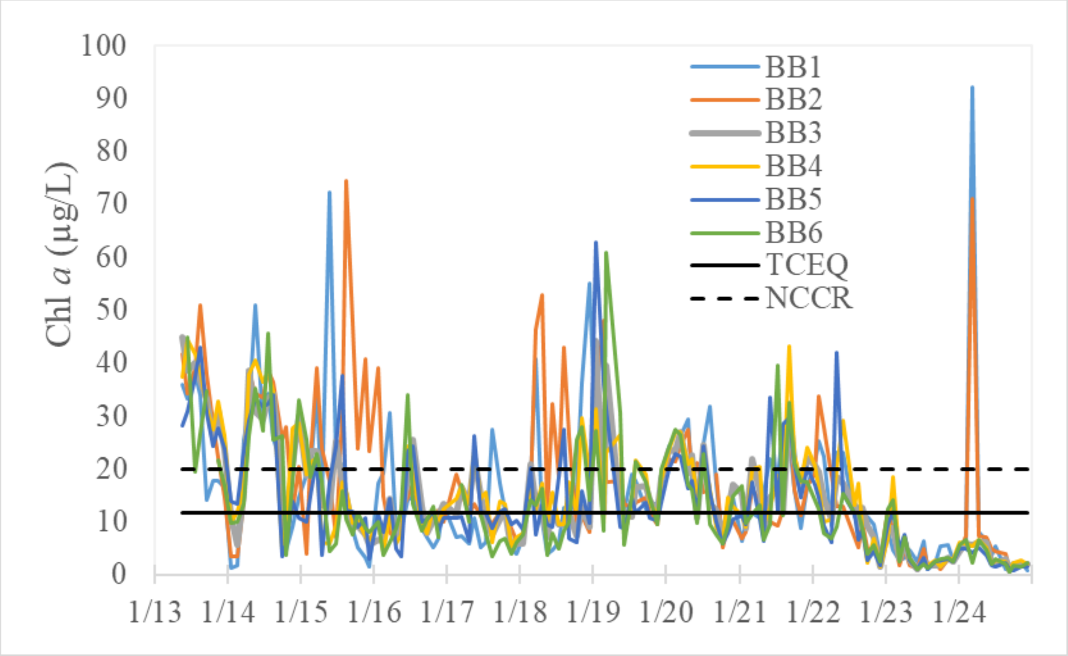

Figure 7. Chlorophyll *a* in Baffin Bay. The solid black line indicates the TCEQ screening level for nutrient concern (11.6 µg/l) while the dashed black line indicates a suggested level that is indicative of eutrophication (20 µg/l).

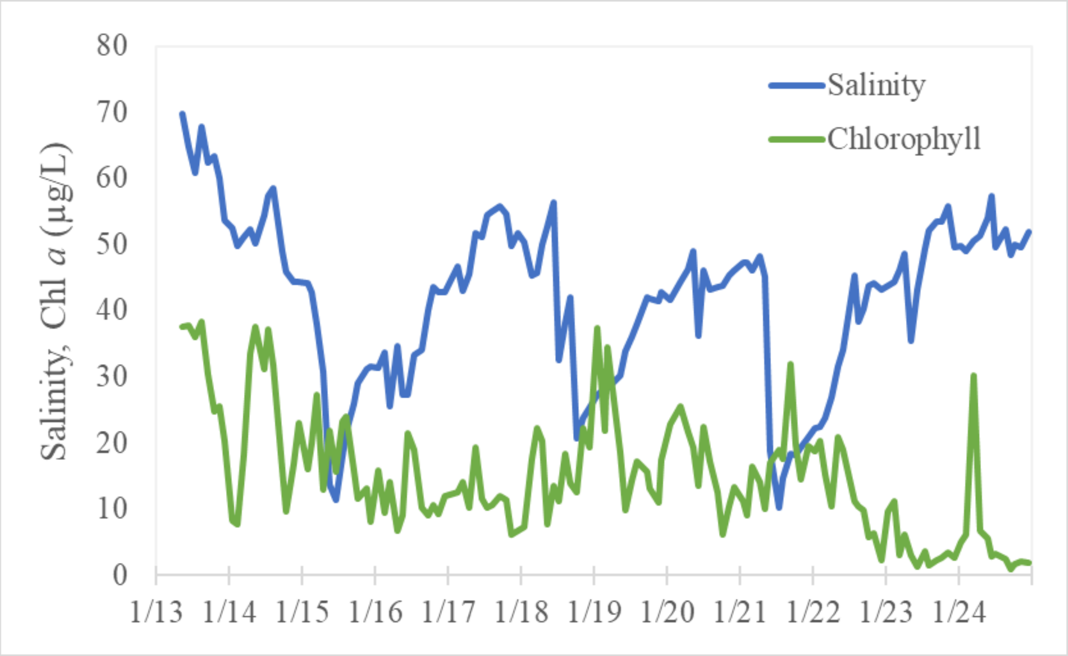

Figure 8. Mean chlorophyll and salinity in Baffin Bay.

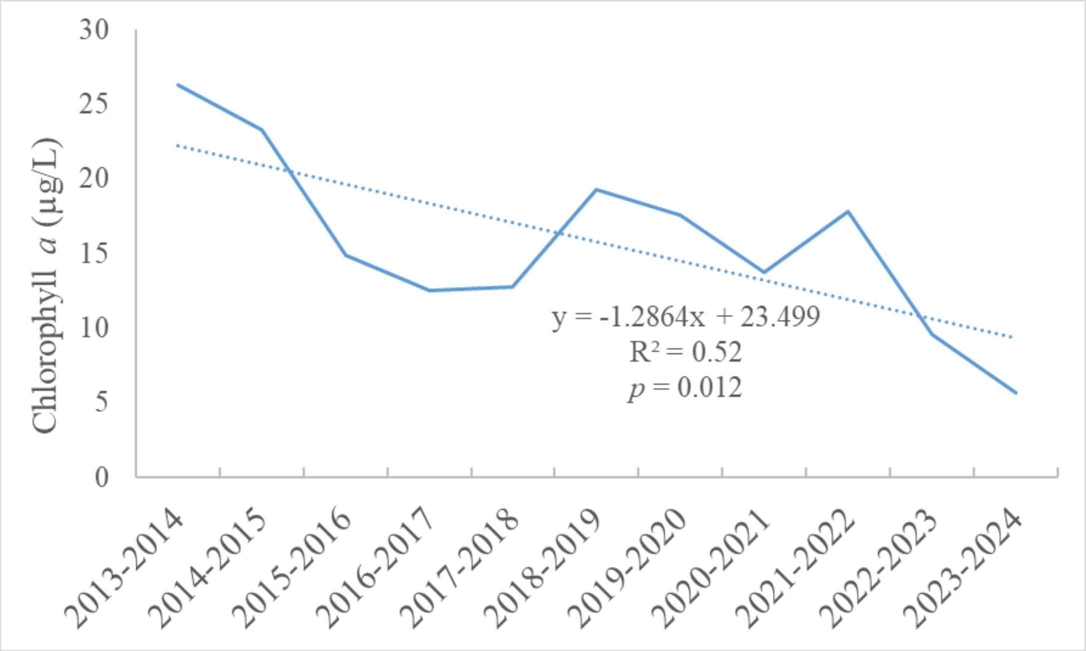

Figure 9. Trend in the annual mean chlorophyll *a* concentration in Baffin Bay.

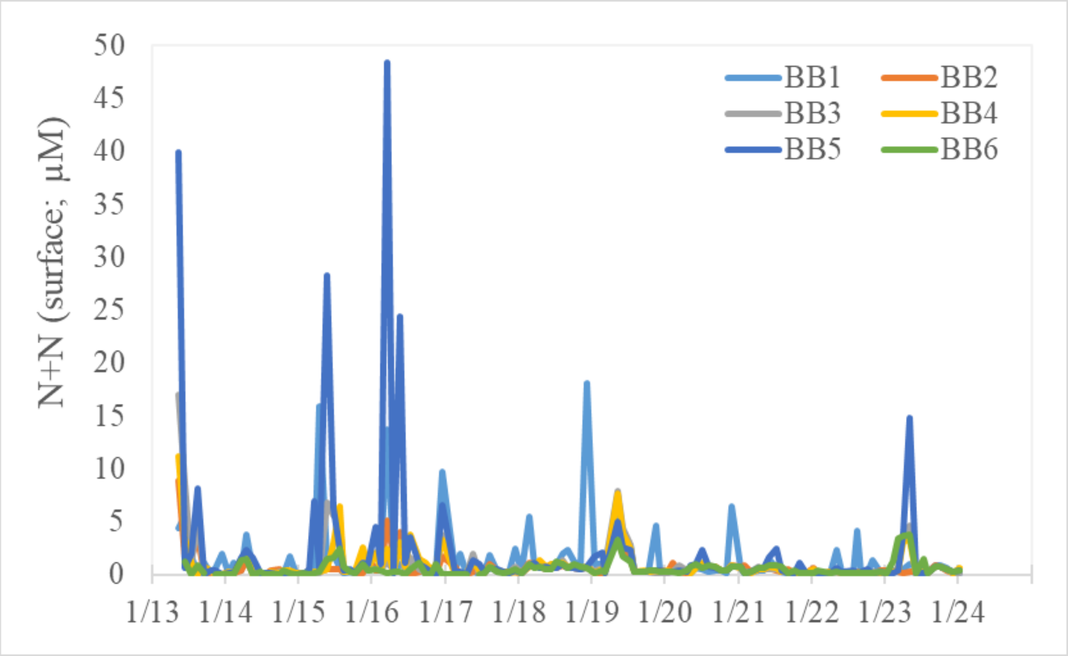

Figure 10. Surface N+N in Baffin Bay.

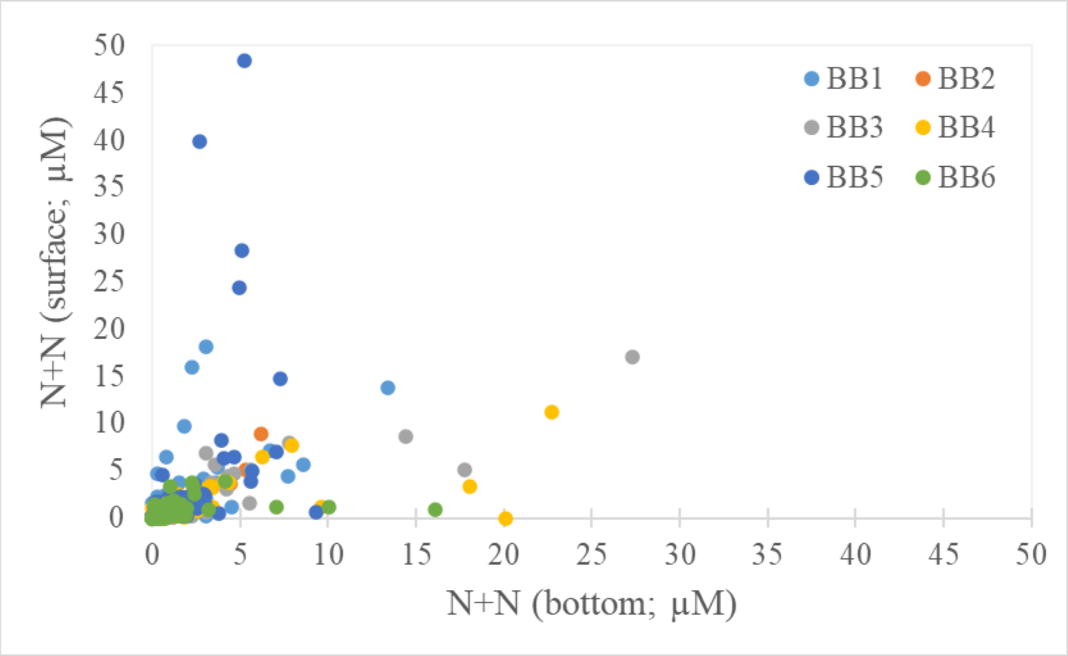

Figure 11. Surface vs. Bottom N+N in Baffin Bay.

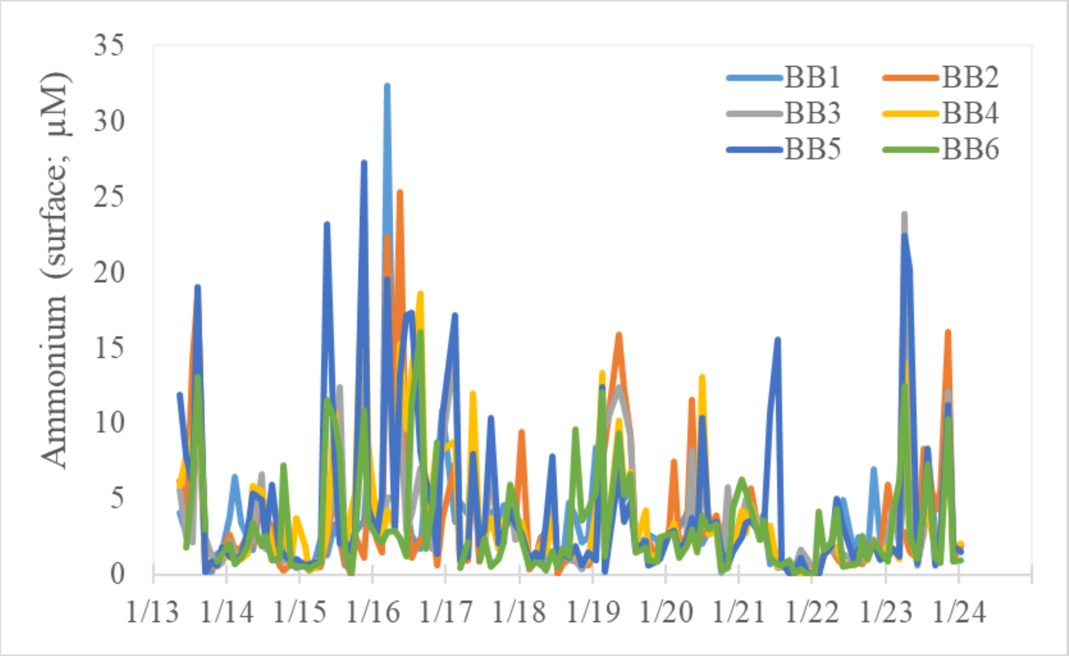

Figure 12. Surface ammonium in Baffin Bay.

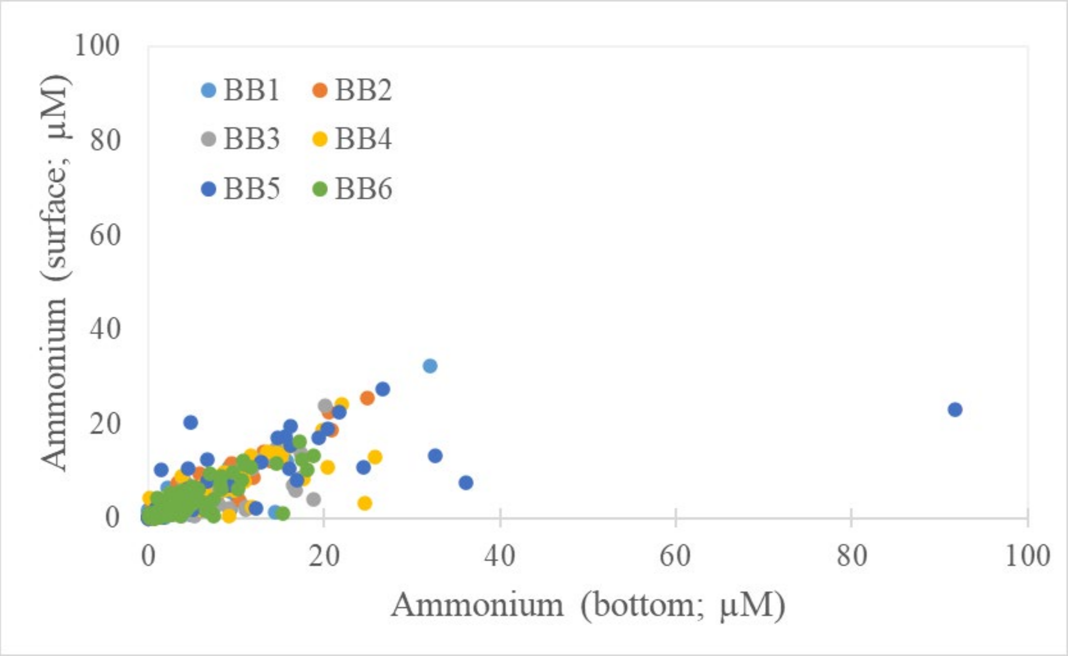

Figure 13. Surface vs. Bottom ammonium in Baffin Bay.

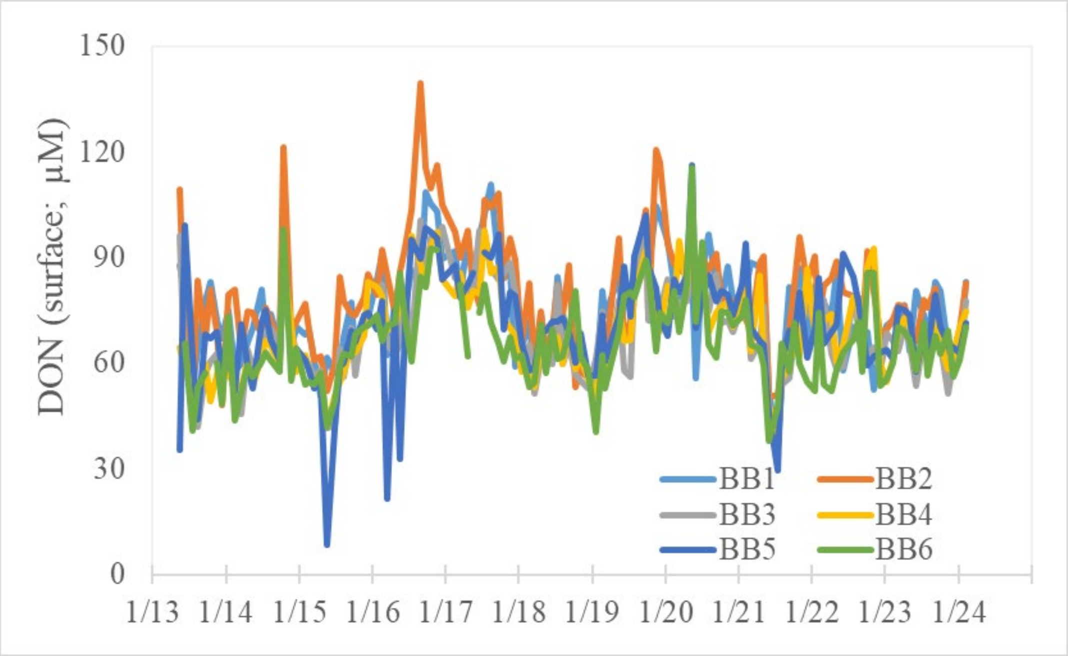

Figure 14. Surface dissolved organic nitrogen in Baffin Bay.

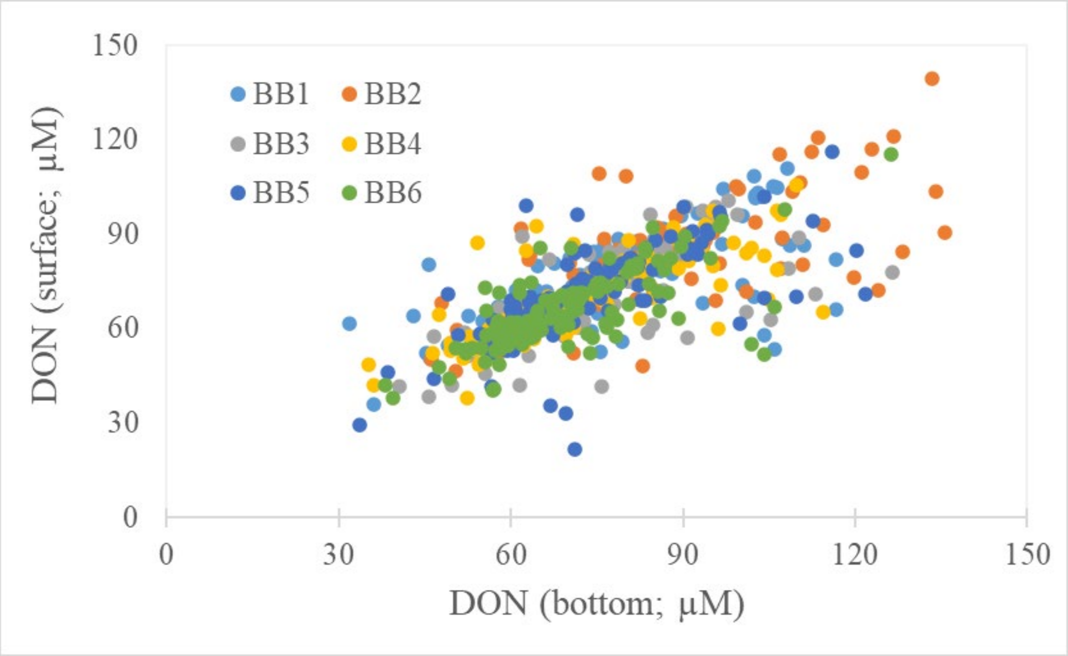

Figure 15. Surface vs. Bottom dissolved organic nitrogen in Baffin Bay.

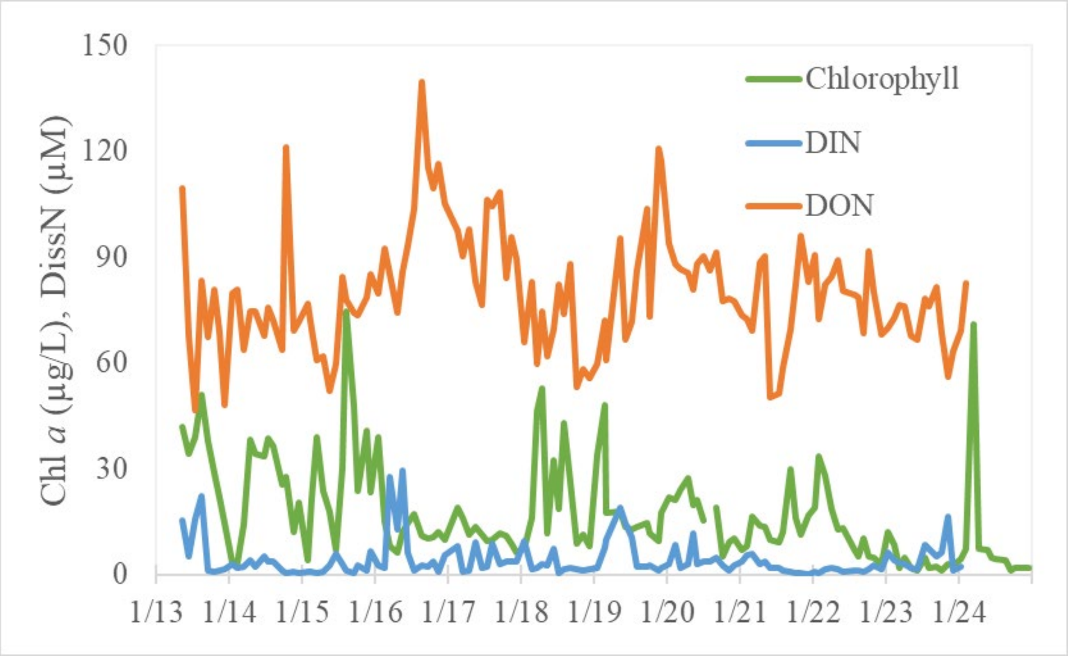

Figure 16. Mean chlorophyll, dissolved organic nitrogen and dissolved inorganic matter at site 2 in Baffin Bay. Note that the same temporal pattern holds for sites 1 and 3-6.

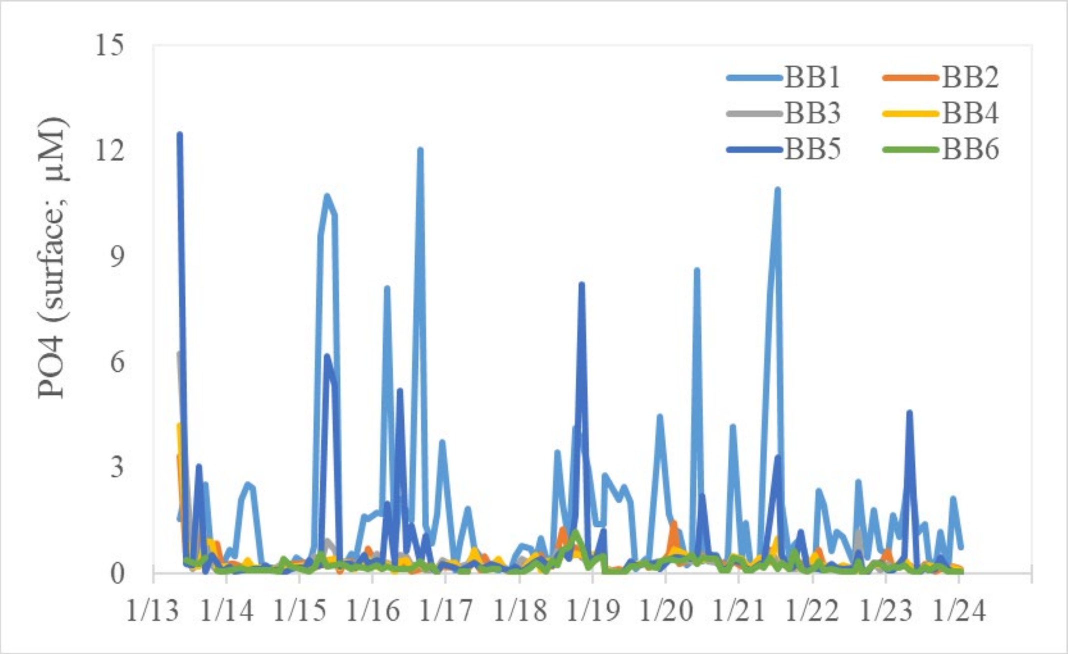

Figure 17. Surface phosphate in Baffin Bay.

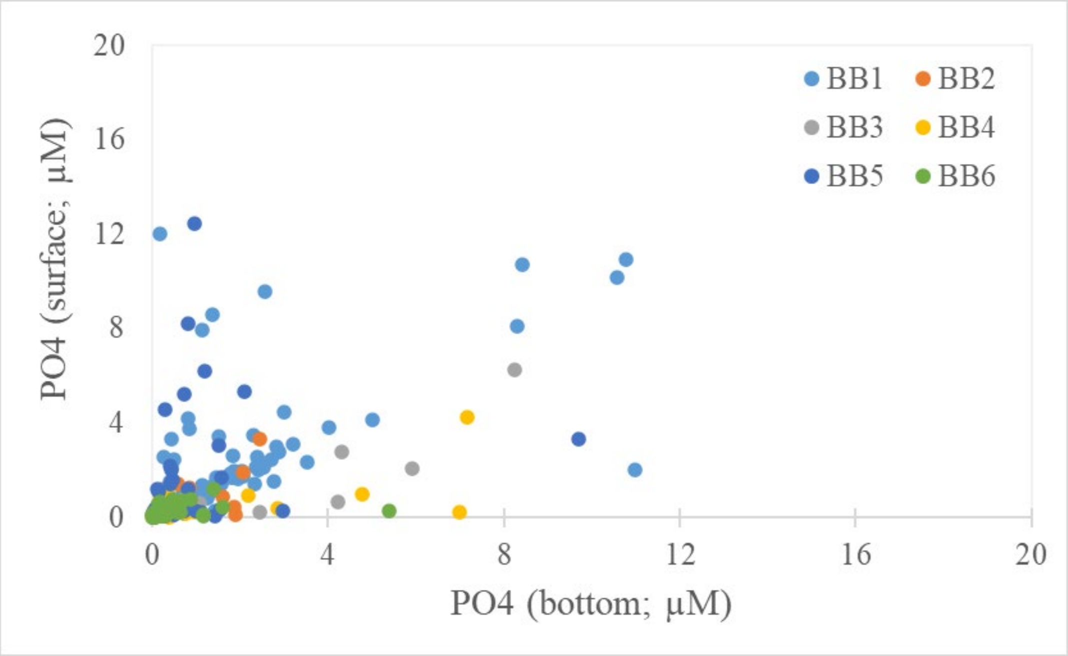

Figure 18. Surface vs. Bottom phosphate in Baffin Bay.

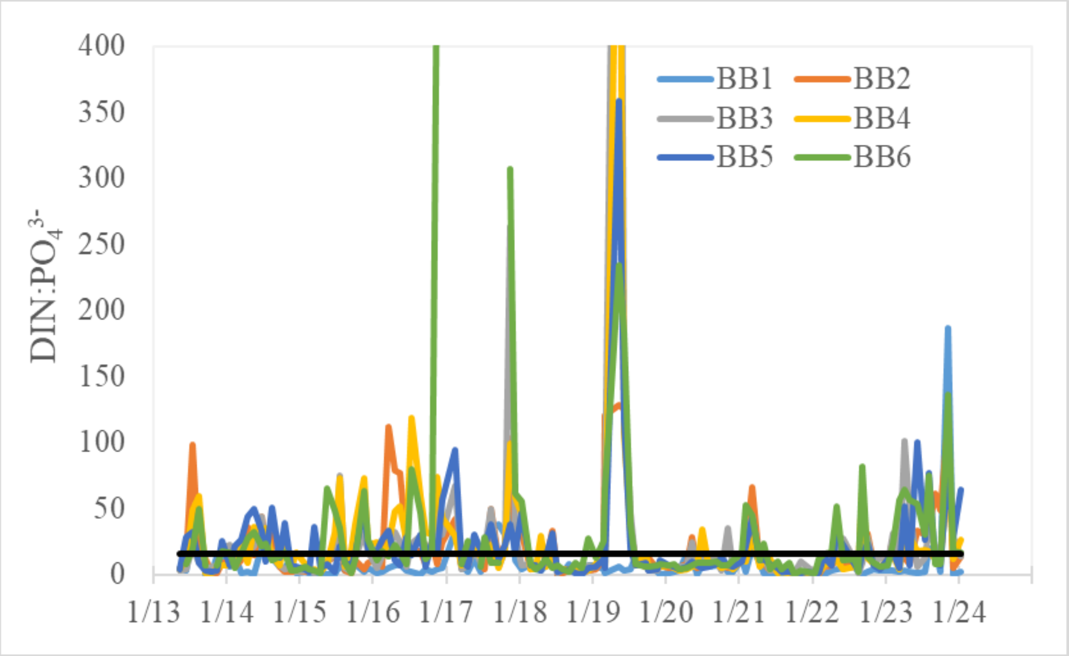

Figure 19. Ratio of inorganic nitrogen to phosphate in Baffin Bay. Solid black line indicates the theoretical boundary between N-limitation (<16) and P-limitation (>16). Note that the following data points exceed the scale: site 6 on 11/17/2016 (488); sites 3 (886) and 4 (626) on 5/13/2019.

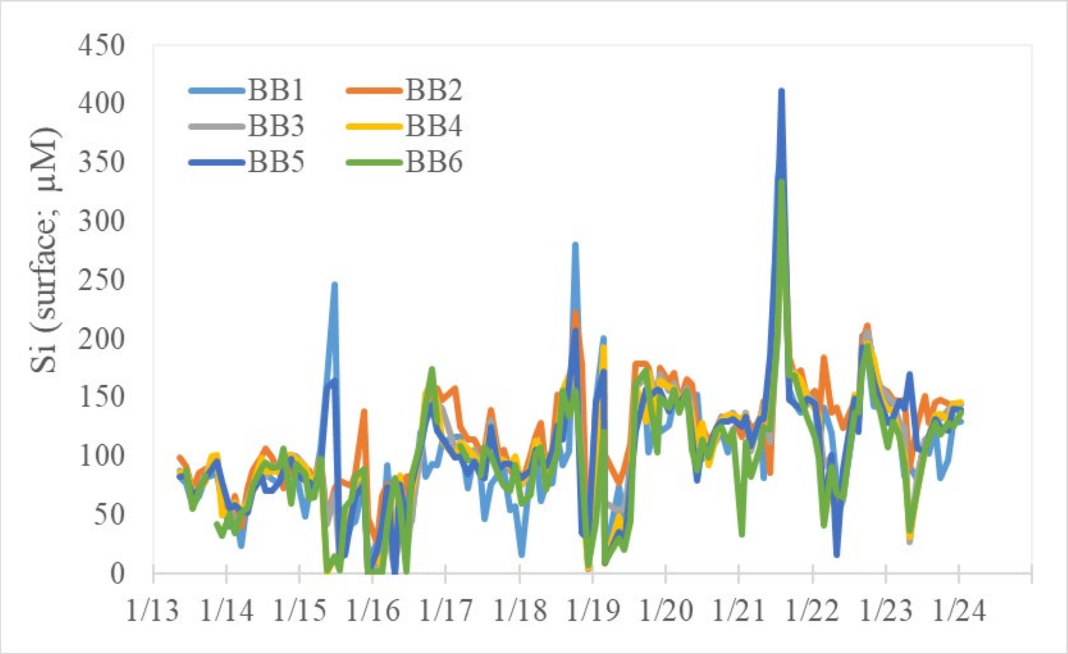

Figure 20. Surface silicate in Baffin Bay.

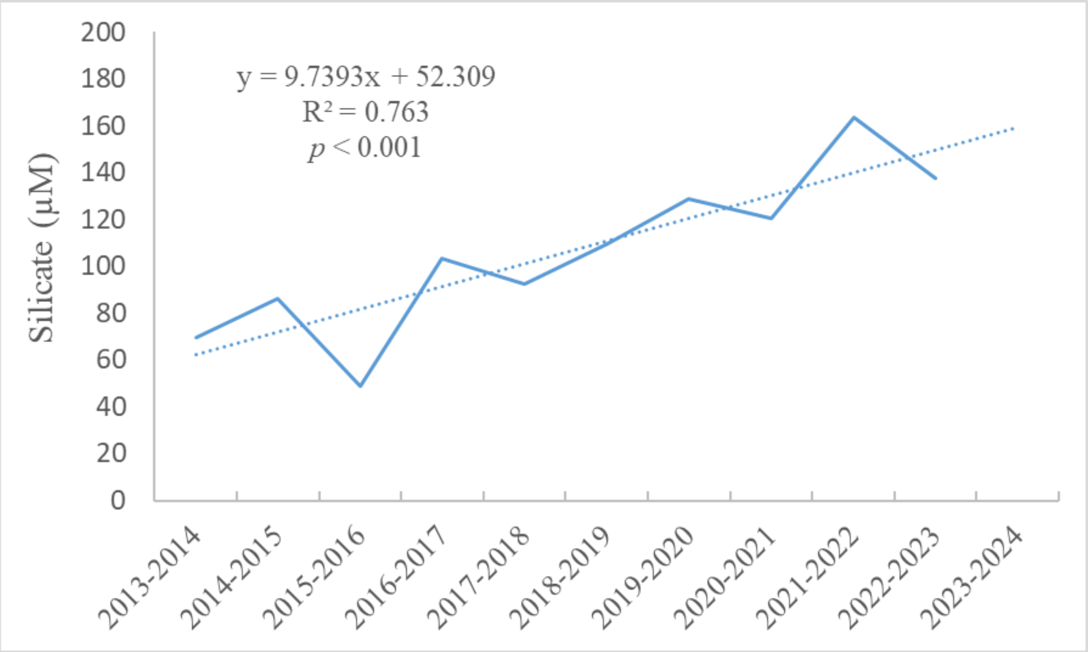

Figure 21. Trend in the annual mean silicate concentration in Baffin Bay.

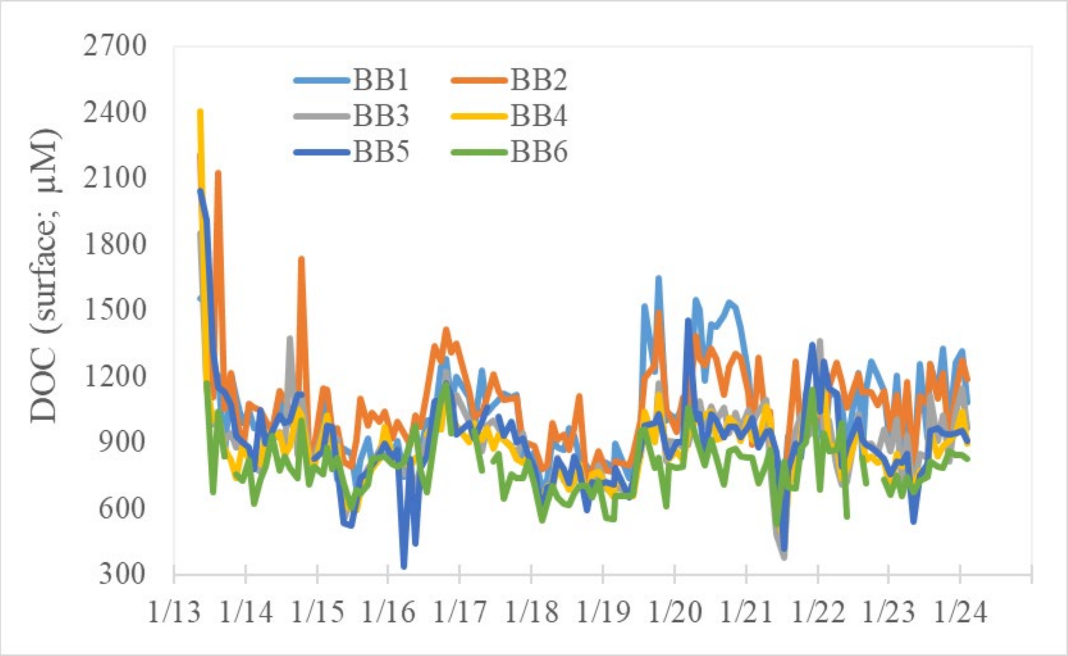

Figure 22. Surface DOC in Baffin Bay.

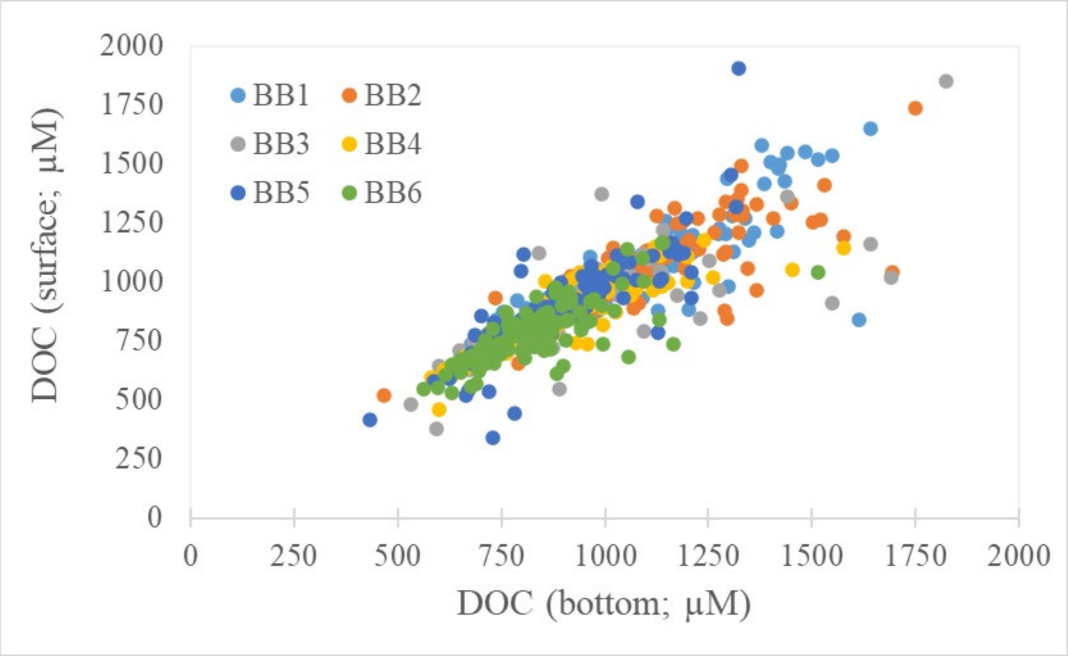

Figure 23. Surface vs. bottom DOC concentrations in Baffin Bay.

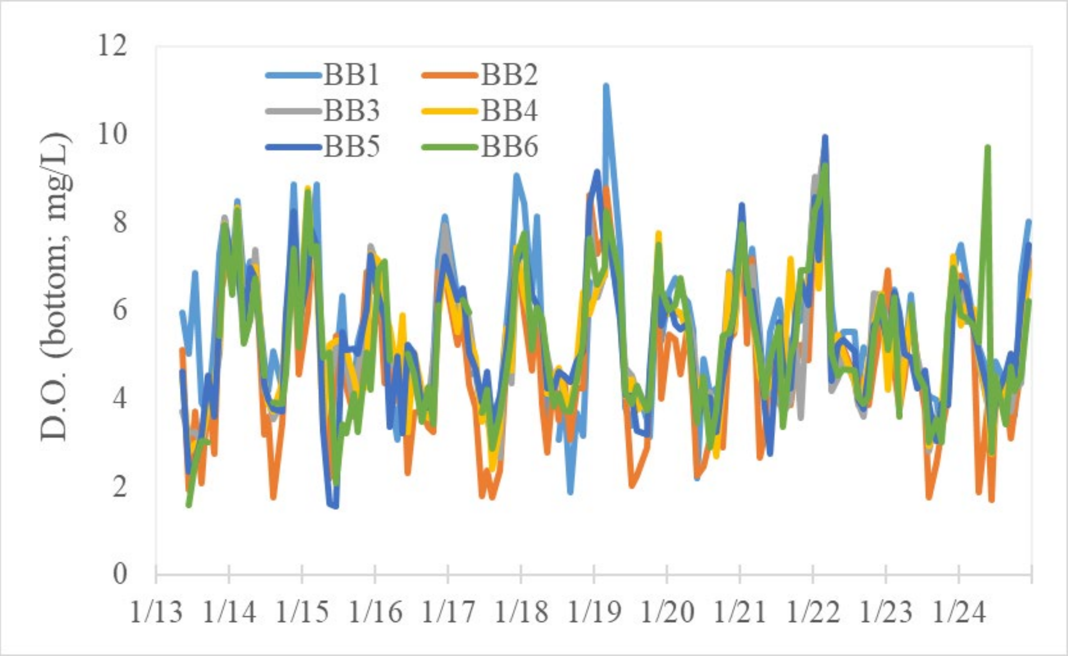

Figure 24. Bottom dissolved oxygen in Baffin Bay.

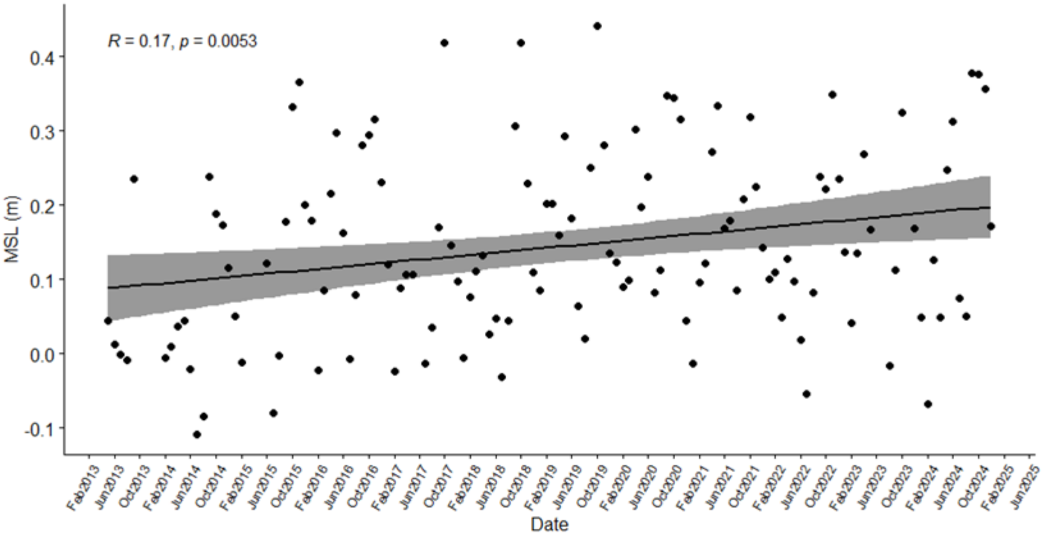

Figure 25. Change in water level over the course of the study period. Note that the annual rate of change was statistically significant at *p* = 0.005 and equated to ~9 mm/year.