

Variations in the physico-chemical properties of San Juan Channel during fall season
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Abstract

Variations in the physical and chemical properties of seawater greatly impact the diversity of organisms that live in the world's ocean and marine ecosystems. Physical and chemical oceanographic properties such as temperature, salinity, dissolved oxygen (DO), and nutrients also serve as indicators of ocean and ecological health. In the San Juan Channel (SJC), previous research has provided the variation and effects of these factors individually e.g. temperature and salinity alone, or with either oxygen or nutrients, but not all together. The goal of this research then was to fill this knowledge gap, in addition to continuing the 20-year-long data of understanding the spatiotemporal variations of these parameters and to fit this year's data with confirmed seasonal and interannual trends. Temperature and salinity data were collected using CTD while dissolved oxygen and nutrient samples were collected using Niskin bottles. Data from 2004-2024 were analyzed using multiple correlation and principal component analysis (PCA). Using PCA, this study confirmed that the water mass from the upper 50 m of North station is coming from the mixing of Strait of Juan de Fuca and Strait of Georgia, which has low nitrogen and phosphate and high DO and silicate. Meanwhile, the bottom depths of South station have its water mass attributed to the surface Pacific or mid Pacific waters, which has high nutrients and low DO. The dynamic mixing activities present in the bottom depths of North station and upper 50 m of South station show that the water masses are coming from the mixing of Strait of Juan de Fuca, Strait of Georgia, and surface Pacific waters, which indicate that the physical and chemical characteristics can also vary spatially and temporally. These findings suggest that PCA is a powerful analysis tool that can be used to identify water masses in the San Juan Archipelago using the relationship of the conservative and non-conservative tracers. Additionally, this study highlights the importance of continuous monitoring in this region as it provides an extensive idea of what is happening in the channel. Understanding how these properties can determine the dynamics of this unique system is crucial to oversee and predict future conditions such as warming, hypoxia, and eutrophication, and to manage the ecosystem and resources of this region.

1. Introduction

Variations in the physical and chemical properties of seawater greatly impact the diversity of organisms that live in the world's ocean and marine ecosystems. Temperature, salinity, and density are the main physical factors that control the world's ocean circulation (i.e., thermohaline circulation) while dissolved oxygen and nutrients are crucial elements needed to support photosynthesis, respiration, and primary production (Webb, 2019). Thus, these factors are also considered as critical controls and indicators of regional and global ocean health and biodiversity (Dodds, 2006).

In the Pacific Northwest, the Salish Sea is the interconnecting marine water system situated between Washington and British Columbia and extends from the northern part of Strait of Georgia down to the southern end of Puget Sound and west to the Strait of Juan de Fuca (Jones et al., 2021; Sutherland et al., 2011). The area is known to be prone to fluctuations in water movement attributed to the Pacific waters entering the Strait of Juan de Fuca and to the freshwater inputs from major rivers such as Fraser River in the northern area of the channel. This creates a complex estuarine circulation that drives changes in the physical characteristics of water and biological activities (Khangaonkar et al., 2019). This particular exchange of strong estuarine flow further develops and in turn brings nutrients from the ocean and flushes the water system in a scale of months (MacCready and Geyer, 2024).

Surrounded by this intricate water system is the San Juan Channel wherein the origin of its waters is known to be primarily from Strait of Juan de Fuca. This body of water is relatively uniform compared to Strait of Georgia where strong signals of freshwater input from the Fraser River are detected. However, due to channel's uneven seafloor and characteristic tidal currents, this creates a unique environment that is home to a rich and diverse ecosystem (Banas et al., 1999; Jones et al., 2021; Phifer and Thompson, 1937). As a result, physical properties such as temperature and salinity and indicators of biogeochemical cycles such as oxygen and nutrients vary spatially and temporally (Phifer and Thompson, 1937). Various regional and global events such as wind-driven processes, fall transition occurrence, tidal exchanges, and El Niño Southern Oscillation (ENSO)

also alter the physical properties and the biogeochemical conditions in this region (Yasunaka et al., 2014).

The Pelagic Ecosystem Function (PEF) apprenticeship program began in 2004 and has been collecting and monitoring oceanographic data in the San Juan Channel every fall season, which has built essential information on the water dynamics of this system. For the most part, previous research has provided the variation and effects of these factors individually e.g. temperature and salinity alone, or with either oxygen or nutrients, but not all together. This means that no PEF study has been able to establish the relationship between all of these factors in this region. The goal of this research then was to fill this knowledge gap using a dimensionality reduction analysis called principal component analysis (PCA). Additionally, this study also aims to continue the 20-year-long data of understanding the spatiotemporal variations of the physical and chemical properties and to fit this year's data with confirmed seasonal and interannual trends. Understanding how these processes can determine the dynamics of this unique system is crucial to oversee future conditions such as warming, hypoxia, and eutrophication, and to manage the ecosystem and resources of this region.

2. Methods

2.1. Data/sample collection

Oceanographic data were collected at Stations North and South once per week from October 1 – November 5 aboard the *R/V Kittiwake* (except for October 1 which used *R/V Rachel Carson*; Figure 1). The water column profile at each station was recorded using a CTD Rosette with built-in Autonomous Firing Module (AFM), composed of a SeaBird SBE 19plus that recorded the temperature, salinity, and depth profiles, and Niskin bottles that collected water samples for dissolved oxygen and nutrients (nitrate, nitrite, ammonium, phosphate, silicate) at discrete depths.

Dissolved oxygen samples were collected first from Niskin bottles to ensure minimal exposure to the atmosphere. Plastic tubing was placed on each specific Niskin bottle spigot to further decrease chances of air exposure. Samples were placed in pre-washed glass bottles and treated with 1 mL

of manganese chloride and 1 mL of sodium hydroxide – sodium iodide solution using burette dispensers to fix the oxygen in the form of a precipitate. After treatment, bottles were carefully closed with glass stoppers and inverted 15 times in two intervals, one right after treatment and another after an hour. These were stored in a wooden box until further laboratory analysis.

Nutrient samples were collected and filtered onboard using pre-washed disposable syringe and 25mm 0.45 micron pore size syringe filters. Filtered samples were placed in pre-washed 60mL HDPE samples bottles up to two-thirds capacity to anticipate water expansion when placed in the freezer. These were stored in a cooler with ice and then frozen until further analysis.

2.2. Data/sample processing

Conductivity, temperature, and depth (CTD)

CTD raw files in hex format were extracted after every cruise using Seasave software. These were converted to cnv format using SBEDataProcessing software following the FHL CTD SBE19plus System Use protocol (Newton, 2009). Only downcast data were saved to be used for further analysis since this represents measurements of an undisturbed water column as opposed to the upcast data which would have perturbations and may have influence on the recorded data. The downcast cnv files were directly loaded in R and converted to csv format for general use.

Dissolved oxygen

Samples for dissolved oxygen were analyzed using a Metrohm Eco Dosimat following the Winkler titration principle which uses sodium thiosulfate as the titrant, potassium iodate as the standard, and starch as the indicator. Standards were run through until a ± 0.001 mL difference were obtained for accuracy. Blanks were titrated twice to obtain a correction blank for precision.

Nutrients

Samples for dissolved nutrients (nitrate, nitrite, ammonium, phosphate, and silicate) were analyzed at the University of Washington Marine Chemistry Lab.

Data analysis

Depth profiles and temperature-salinity diagrams were visualized using OceanDataView software and R data analysis software. Welch's *t*-test was used to compare means between stations and between depths of dissolved oxygen and nutrient concentrations. Multiple correlation analysis and principal component analysis (PCA) were also performed using R software.

3. Results

3.1. Physical properties

Depth profiles

The temperature and salinity depth profiles described that the North station had a well-mixed water column for fall 2024, with slight stratification observed during October 1 and October 7 cruises (Figure 2). In contrast, South station had a more stratified water column along with a shallowing of the thermocline and halocline shallowing during October 8 and October 15 sampling events (Figure 2).

As the fall season progressed, the recorded temperature values for the whole water column decreased from 11°C to 10°C, while salinity increased from 30 to 31 PSU for North station (Figure 2). The same trend was observed for South station, wherein temperature decreased from 11°C to less than 10°C, while salinity increased from 31 to 31.5 PSU. There was also a noticeable weakening of stratification at South station depicted by the shapes of the temperature and salinity profiles, i.e. the profiles became more uniformly vertical (Figure 2).

Water masses

Using temperature-salinity diagrams and designations from Redfield (1950), the identities of water masses present this season were described. North station showed two different water masses at two different depth ranges: the upper 50 m of the water column may be attributed from the mixing of Strait of Juan de Fuca and Georgia Strait while the bottom depths were coming from the mixing of Strait of Juan de Fuca, Georgia Strait, and surface Pacific Ocean waters (Figure 3). For South station, four water masses were observed at three different depth ranges: the upper 30 m coming from the mixing of Strait of Juan de Fuca and Georgia Strait, the mid-depth (30-50 m) from the mixing of Strait of Juan de Fuca, Georgia Strait, and surface Pacific Ocean waters, and the bottom depths (50-80 m) from the surface Pacific Ocean waters or mid Pacific Ocean waters (Figure 3). Looking at the temperature-salinity diagrams from 2004-2024, fall 2024 followed the same water masses observed throughout previous years (Figure 3).

3.2. Chemical properties

The interannual variability of chemical oceanographic properties such as dissolved oxygen, dissolved inorganic nitrogen (DIN, nitrate + nitrite + ammonium), phosphate, and silicate at the surface and bottom depths at North and South stations were visualized using boxplots. Only CTD data were collected during 2004 while dissolved oxygen data were not available during 2015 and 2019.

Dissolved oxygen (DO)

Dissolved oxygen concentrations ranged from 3-8 mg/L at both stations (Figure 4). North station consistently had higher DO concentrations than South station, but there was no difference in DO concentrations at the surface between stations (Figure 4). The highest surface DO concentrations at both stations were measured in 2011, while this year's data showed the lowest values of bottom DO at both stations (Figure 4). Higher range values were observed during 2009 and 2014 at South station, both bottom and surface depths (Figure 4).

Nutrients

North and South stations display uniform patterns of average dissolved oxygen and nutrient concentrations between surface and bottom depths (Table 1). South station has less dissolved oxygen but with more nutrients compared to North station. Consequently, bottom waters also have less dissolved oxygen but with more nutrients compared to the surface waters (Table 1).

Dissolved inorganic nitrogen values range from 20-30 μM , with moderate to low variability throughout 2005-2024 (Figure 5). Around 2005-2011, minimal changes in DIN values were observed at both stations and at both depths. However, around 2012, higher variability was observed at surface depths for both stations, which continued until 2015 (Figure 5). The same trend was observed during 2019, followed by a much higher variation in 2022. This year, surface DIN values have the same higher than usual variation at North and South stations. Overall, South station has more DIN at bottom depths compared to North station while no difference between the two stations were observed at surface depths.

Phosphate concentrations range from 1.3-3.0 μM , and showed the same moderate to low variabilities as DIN (Figure 6). The most variation in surface depths was measured in 2005 and 2022 at both stations and the most variation in bottom depth concentrations at both stations was measured in 2022. Variations in surface phosphate levels at North station were also observed during 2012, 2013, and 2015. This year, surface phosphate concentrations have the same moderate variation at both stations. Overall, North station has more phosphate at bottom depths compared to South station while no difference at surface depths was observed between two stations

Silicate distributions had less variability in concentrations relative to other nutrients, both at the surface and at the bottom of North and South stations. Values range from 30-60 μM , with a decreasing trend from 2005-2024. The exception to this conservative behavior was in 2013, which showed high variations at surface and bottom depths for both stations (Figure 7). Variations were also observed during year 2012 at the surface of North station. The highest silicate concentration recorded was at 2007 at the bottom depth of North station, while year 2008 showed the highest concentration at bottom depth of South station (Figure 7).

3.4. Multiple correlation

A multiple correlation analysis was performed to initially explore the relationship between the physical and chemical oceanographic properties (Figure 8). The following strong correlations were observed ($r = \pm 0.60$): temperature vs. salinity (-0.72), temperature vs. phosphate (-0.63), salinity vs. phosphate (0.64), temperature vs. nitrate (-0.81), salinity vs. nitrate (0.71), oxygen vs. nitrate (-0.63), phosphate vs. nitrate (0.80). Moderate correlations ($r = \pm 0.30$) were also observed among the following variables: depth vs. temperature, salinity, oxygen, nitrate; silicate vs. temperature, phosphate; nitrite vs. temperature, salinity, oxygen, silicate; and ammonium vs. temperature, silicate, phosphate, nitrate.

3.5. Principal component analysis

The linearity obtained from multiple correlation analysis was used as a basis to perform principal component analysis (PCA). Figures 9, 10, and 11 showed the resulting PCA plots based on the contribution of variables and individuals to the principal components. PCA shows that nitrate, temperature, salinity, phosphate, and oxygen contributed the most to principal component 1 (PC1) in decreasing trend. Meanwhile, ammonium, depth, nitrate, and silicate contributed to principal component 2 (PC2) with ammonium accounting for almost 40% of the total contribution. Overall, a total of 64% of the combined variations were accounted from the two components, with 49.95% from PC1 and 14.44% from PC2. Figure 10 shows that the samples from North and South stations were mostly overlapping.

4. Discussion

Physical properties

As fall season progressed from October 2 to November 5, water column temperature decreased from 11 to 10 °C for both stations, which in turn, increased the salinity from 30 to 31 PSU. This

can be attributed to the fact that when water cools or lowers its temperature, it becomes more denser, which then increases salinity (Pond and Pickard, 1983).

For fall this year, the differences in vertical profiles between the two stations were distinct (Figure 2). At North station, a very well-mixed water column was observed during the course of sampling, which was indicative of dynamic mixing activities occurring in the area. This well-mixed column can be advantageous as it allows easy vertical movement of plankton and nutrients and other organisms throughout the column, which can then increase primary productivity (Huisman and Weissing, 1995).

On the other hand, South station has a more stratified water column which was also observed in previous studies. This stratification is expected since the Pacific waters, which are denser, and the water masses with river discharge influence, which are less dense, are mixing in this region. Both temperature and salinity are considered conservative properties, meaning, except at the surface, there are no processes other than mixing that can change these properties (Brown et al., 2001).

External physical processes can also affect pattern changes in temperature and salinity profiles, but will not be explained further in this study. However, previous PEF researches strongly suggested that tides and fall transition played a huge role in the vertical profiles of North and South stations. Temperature fluctuations were observed to be influenced by tidal patterns (Wang, 2022) and fall transition alterations (Cogan, 2014). Salinity was also predicted to be influenced by tidal phases (Parker, 2018). Tides also governed stratifications in the water column, particularly changes in the halocline and pycnocline (Thomas, 2011; Williams, 2012).

Chemical properties

Notably, lower oxygen and higher nutrients were observed at South station and at bottom depths, which can be attributed to the Pacific Ocean waters entering the channel. Based on the global ocean circulation, deep Pacific Ocean waters are considered as “old waters” as they are the end member of thermohaline circulation, meaning their characteristic low oxygen and high nutrients

are due to the fact that they have not been able in contact with the atmosphere for a long period of time (i.e. 1000 years before they resurface again) (Carilli, 2013).

Similarly with the temperature and salinity differences, regional processes can drive changes and variability in the dissolved oxygen and nutrient concentrations of this region. Earlier PEF studies on changes in oxygen and nutrient levels in this area showed different drivers for short- and long-term time scales. Dissolved oxygen levels were altered due to changes in winds and tides (Powers, 2008), as well as coastal upwelling and changes in fall transition timing (Hale, 2017; Josza, 2023; McLaughlin, 2009; Powers, 2008; Rehder, 2016; Rouske, 2019).

Relationship between water masses, dissolved oxygen, and nutrients

The strong correlations between temperature, salinity, dissolved oxygen, nitrate, and phosphate, imply that the nutrients from this channel are coming from the deep Pacific waters. Meanwhile, dissolved inorganic nitrogen constituents have negative correlations with each other, which is attributed to their role in the ocean nitrogen cycle. Nitrate and ammonium are the forms of nitrogen actively used in nitrification, denitrification, and annamox reactions, while nitrite is mostly a transient form of nitrogen in these processes (Voss et al., 2013). Silicate levels may be heavily influenced by river output as evidenced by high concentrations at surface depths, which were also previously observed by Crawford (2022).

Using PCA in this study proved that it is a powerful analysis tool that can be used to find relationships among multiple variables and to group individual samples in large datasets to find distinct patterns. Figure 9 showed the different physical and chemical properties attributed to each water mass type. The samples located in the upper left quadrant, having low DIN and phosphate, high dissolved oxygen, high silicate, high temperature, and low salinity, indicate water masses coming from the mixing of Juan de Fuca, Georgia Strait, and Pacific waters, which can be seen in the whole water column of North station and surface to mid-depth part of South station. On the other hand, samples located in the upper and lower right quadrant may be attributed to the surface and mid Pacific waters, which can only be seen on the deeper part of South station. Overall, PCA analysis mostly showed the overlapping components of individual samples from North and South

stations, which strongly suggests the presence of mixing between Juan de Fuca, Georgia Strait, surface Pacific, and mid Pacific waters, influencing the variations in the chemical constituents of the San Juan Channel.

5. Conclusion

In the San Juan Channel region, variations in temperature and salinity were mainly attributed to topographical differences, seasonal shift from fall to winter, and presence of dynamic mixing of water masses, which is supported by differences between stations, between sampling dates, and statistical analysis. The nutrients in the region were found to be mainly from Pacific Ocean waters, attributed to higher average concentrations at bottom depth with high salinity correlation. Strong signals of water masses mixing were observed for both North and South stations. This study demonstrates the use of principal component analysis (PCA) to identify water masses in the San Juan Archipelago using the relationship of the conservative and non-conservative tracers with each other.

6. Future Directions

Continuous monitoring of the region is essential in determining future ocean conditions, given the projected increase in sea surface temperatures and the possible increase in anthropogenic factors as San Juan Islands is becoming a more popular tourism spot in the state of Washington. This study can be further improved by verifying the influence and relationship of regional events such as tides, winds, and river discharge, as well as global climate events such as El Niño Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) to the physical and chemical properties of San Juan Channel and the whole Salish Sea. The influence of tides can be clearly seen if it will be allowed to conduct substantial diel sampling, while the effect of wind alterations can be seen by studying the fall transition. River discharge effects can be studied by collecting monthly mean discharges of major rivers such as Fraser River, while climate effects can be studied using satellite and remote sensing data. Additional sampling events during spring, summer, and winter would be a great way to gather an all-year round data that can be used to feed into models and predict these future conditions, which can help manage the ecosystem and resources of the channel.

References

- Banas, N., Bricker, J., Carter, G., Gerdes, F., Martin, W., Nelson, E., Ross, T., Scansen, B., Simons, R., & Wells, M. (1999). *Flow, Stratification, and Mixing in San Juan Channel*. https://www.researchgate.net/publication/265529498_Flow_Stratification_and_Mixing_in_San_Juan_Channel
- Brown, E., Colling, A., Park, D., Phillips, J., Rothery, D., & Wright, J. (2001). *Ocean Circulation* (p. 225). Open University.
- Carilli, J. (2013, July 5). Saltwater Science. *How Old Is the Ocean?* https://www.nature.com/scitable/blog/saltwater-science/how_old_is_the_ocean/#:~:text=By%20measuring%20the%20amount%20of,mix%20to%20the%20surface%20again.
- Cougan, C. (2014). *Factors affecting San Juan Channel and Puget Sound water properties during fall 2014*. Pelagic Ecosystem Function Research Apprenticeship Program.
- Crawford, I. (2022). *The Influence of Riverine Inputs and Nutrients on Plankton Abundance and Composition in the Pacific Northwest*. Pelagic Ecosystem Function Research Apprenticeship Program.
- Dodds, W.K. (2006). *Nutrients and the “dead zone”: the link between nutrient ratios and dissolved oxygen in the northern Gulf of Mexico*. *Frontiers in Ecology and the Environment*, 4: 211-217. [https://doi.org/10.1890/1540-9295\(2006\)004\[0211:NATDZT\]2.0.CO;2](https://doi.org/10.1890/1540-9295(2006)004[0211:NATDZT]2.0.CO;2)
- Hale, R. (2017). *A Multiyear Analysis of Aragonite Saturation State and Dissolved Oxygen in San Juan Channel*. Pelagic Ecosystem Function Research Apprenticeship Program.
- Huisman, J., & Weissing, F. J. (1995). Competition for Nutrients and Light in a Mixed Water Column: A Theoretical Analysis. *The American Naturalist*, 146(4), 536–564. <https://doi.org/10.1086/285814>
- Jones, J., Keller, P., & Keller, E. van der F. (2021). Review of official responsibility for the Salish Sea marine environment. *Ocean & Coastal Management*, 211, 105748. <https://doi.org/10.1016/j.ocecoaman.2021.105748>
- Josza, E. (2023). *Water Properties in the San Juan Archipelago in Fall 2023*. Pelagic Ecosystem Function Research Apprenticeship Program.

- Khangaonkar, T., Nugraha, A., Xu, W., & Balaguru, K. (2019). Salish Sea Response to Global Climate Change, Sea Level Rise, and Future Nutrient Loads. *Journal of Geophysical Research: Oceans*, 124(6), 3876–3904. <https://doi.org/10.1029/2018JC014670>
- MacCready, P., & Geyer, W. R. (2024). Estuarine Exchange Flow in the Salish Sea. *Journal of Geophysical Research: Oceans*, 129(1), e2023JC020369. <https://doi.org/10.1029/2023JC020369>
- McLaughlin, R. (2009). *Inter-annual variation in temperature, salinity, and dissolved oxygen in San Juan Channel: Patterns and external driving forces*. Pelagic Ecosystem Function Research Apprenticeship Program.
- Meyer, B. (2011). *Factors influencing phytoplankton and dissolved oxygen in San Juan Channel: A spatial and temporal assessment*. Pelagic Ecosystem Function Research Apprenticeship Program.
- Newton, J. (2009). *FHL CTD SBE19plus System Use Protocol*.
- Parker, Z. (2018). *Fraser River Influence on the Northern San Juan Channel*. Pelagic Ecosystem Function Research Apprenticeship Program.
- Phifer, L., & Thompson, T. (1935). Seasonal variations in the surface waters of San Juan Channel during the five year period, January 1931 to December 30, 1935. *Journal of Marine Research*, 1(1). https://elischolar.library.yale.edu/journal_of_marine_research/518
- Pond, S., & Pickard, G. L. (1983). *Introductory Dynamical Oceanography* (2nd ed.). Pergamon Press.
- Powers, K. (2008). *Physical and biological factors affecting dissolved oxygen concentrations in the San Juan Channel, WA on a spatial and temporal scale during fall 2008*. Pelagic Ecosystem Function Research Apprenticeship Program.
- Redfield, A.C. (1950). *Note on the circulation of a deep estuary: the Juan de Fuca-Georgia Straits. Proceedings of the Colloquium on the Flushing of Estuaries*. Woods Hole Oceanographic Institution.
- Rehder, B. (2016). *Determining tidal influence on dissolved oxygen in the San Juan Channel*. Pelagic Ecosystem Function Research Apprenticeship Program.
- Rouske, J. (2019). *A Multiyear Analysis of Dissolved Oxygen and pH in the San Juan Archipelago*. Pelagic Ecosystem Function Research Apprenticeship Program.

- Sutherland, D. A., MacCready, P., Banas, N. S., & Smedstad, L. F. (2011). A Model Study of the Salish Sea Estuarine Circulation. *Journal of Physical Oceanography*, 41(6), 1125–1143. <https://doi.org/10.1175/2011JPO4540.1>
- Thomas, K. (2011). *Seasonal and tidal effects on water density gradients in the San Juan Channel*. Pelagic Ecosystem Function Research Apprenticeship Program.
- Voss, M., Bange, H.W., Dippner, J.W., Middelburg, J.J., Montoya, J.P., Ward, B. (2013). *The marine nitrogen cycle: recent discoveries, uncertainties and the potential relevance of climate change*. *Philos Trans R Soc Lond B Biol Sci*. 2013 May 27;368(1621):20130121. doi: 10.1098/rstb.2013.0121. PMID: 23713119; PMCID: PMC3682741.
- Wang, F. (2022). *Physical Water Properties and Impacts of Winds in the San Juan Archipelago*. Pelagic Ecosystem Function Research Apprenticeship Program.
- Webb, P. (2019). *Introduction to Oceanography*. Rebus Community.
- Williams, K. (2012). *Spatial and temporal variation in hydrography, chlorophyll, and oxygen of San Juan Channel: Effects of local and external factors*. Pelagic Ecosystem Function Research Apprenticeship Program.
- Yasunaka, S., Nojiri, Y., Nakaoka, S., Ono, T., Whitney, F. A., & Telszewski, M. (2014). Mapping of sea surface nutrients in the North Pacific: Basin-wide distribution and seasonal to interannual variability. *Journal of Geophysical Research: Oceans*, 119(11), 7756–7771. <https://doi.org/10.1002/2014JC010318>

Figures and Tables

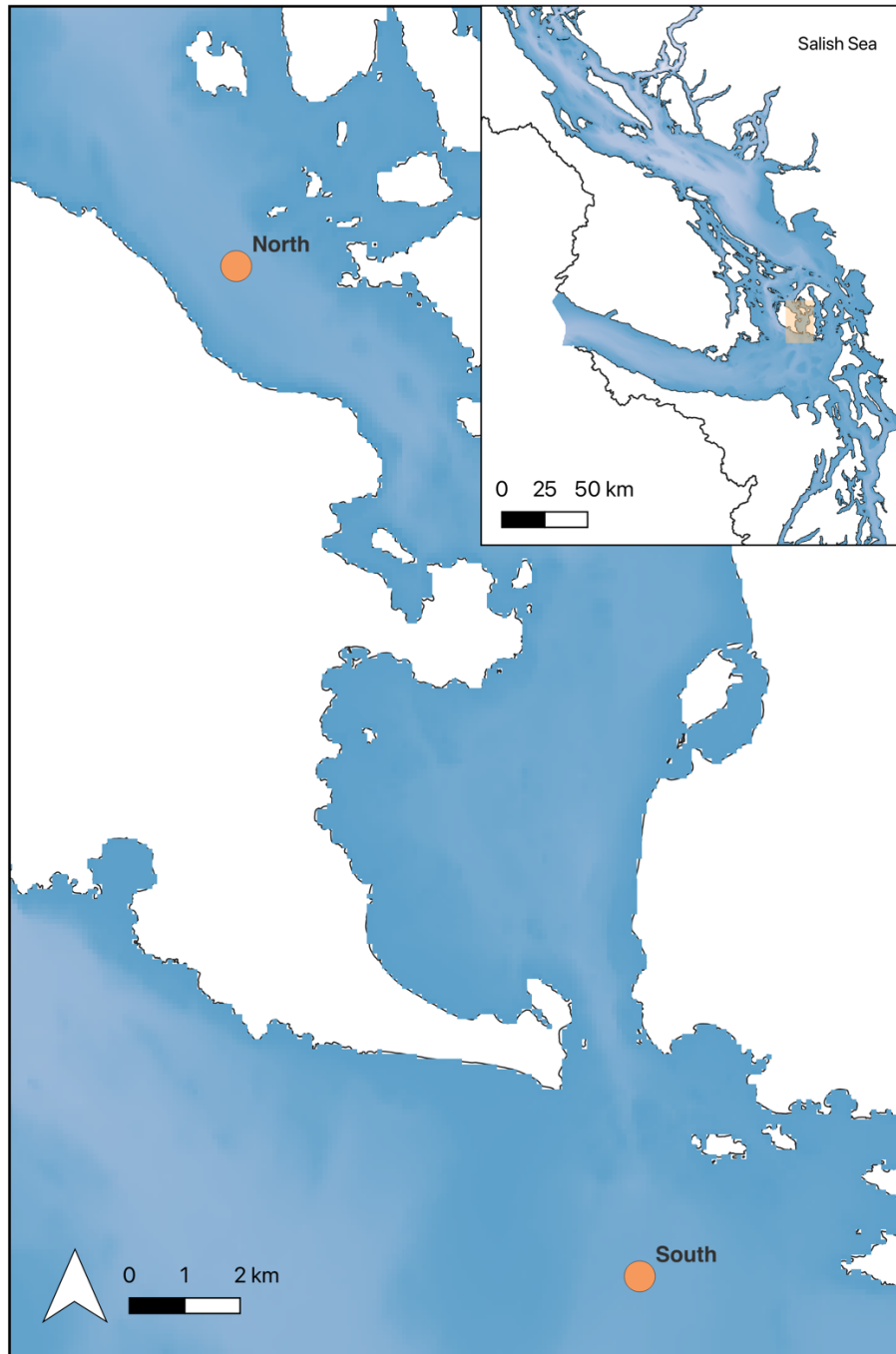


Figure 1. Sampling stations indicated by orange dots: North Station (N, 48°35' N, 123°02' W) and South Station (S, 48°25' N, 122° 56' W).

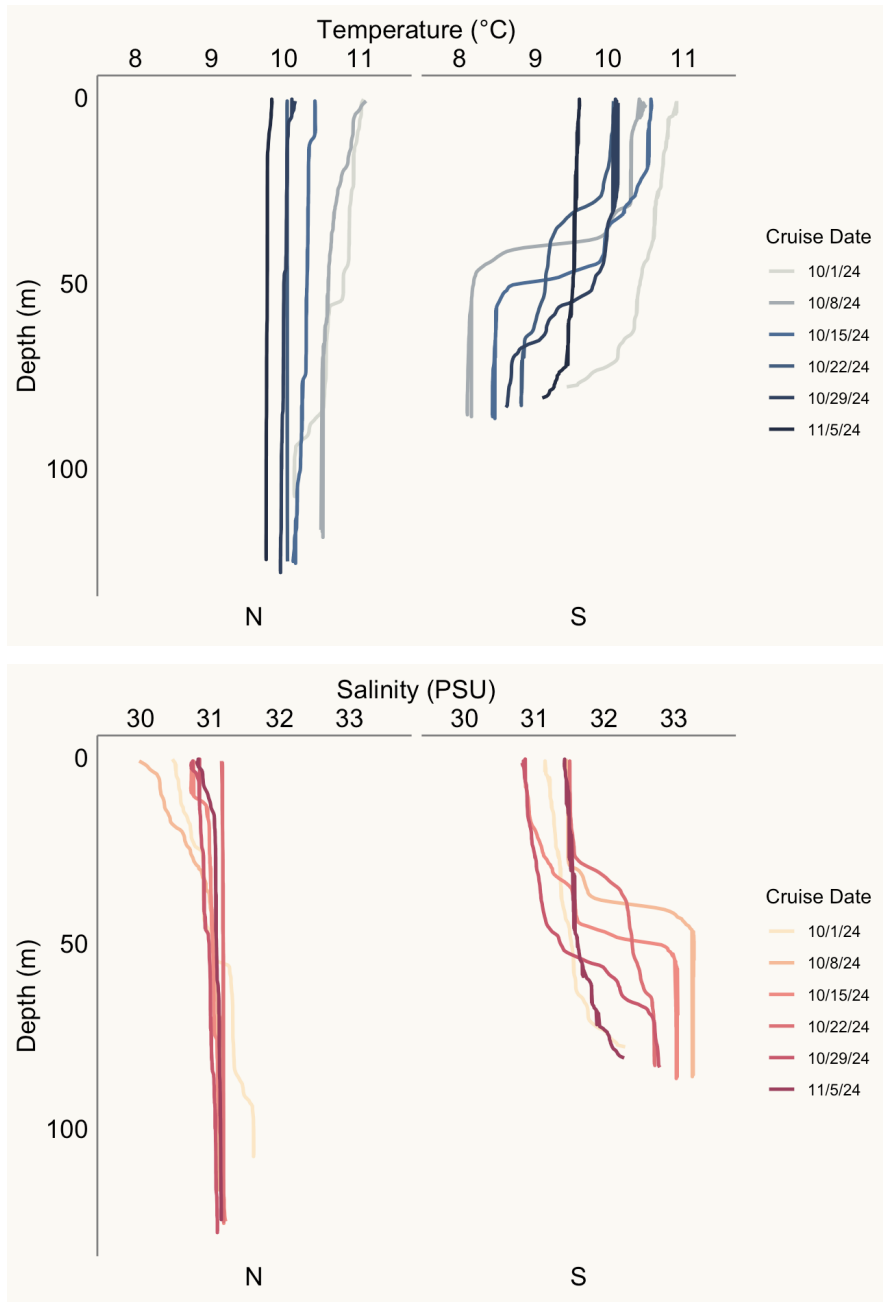


Figure 2. Temperature (top) and salinity (bottom) depth profiles during fall 2024. Cruise dates are indicated by colors.

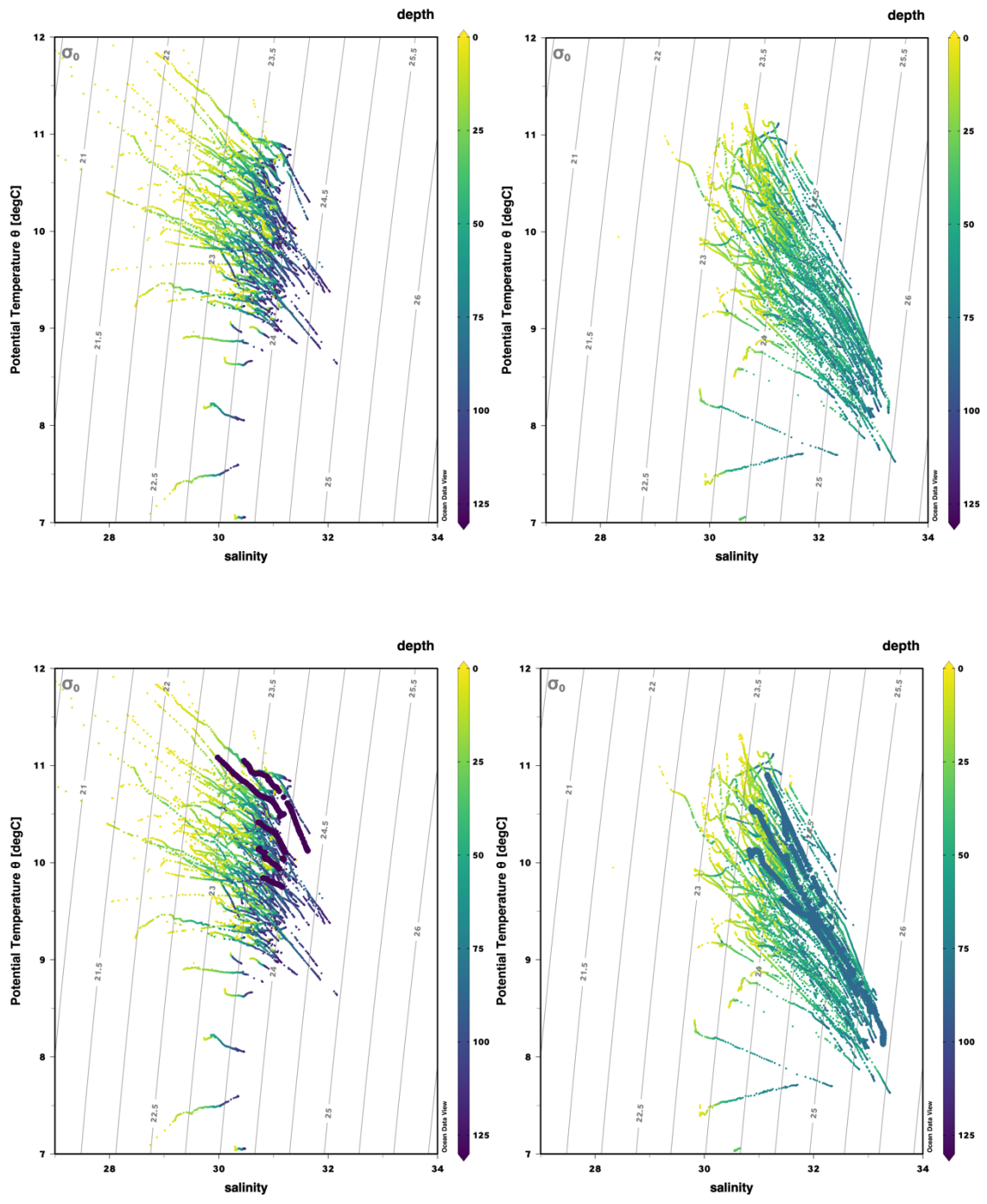


Figure 3. Temperature-salinity diagrams of North (left) and South (right) stations in relation to depth. Density lines are marked as isopycnals. Highlighted points refer to fall 2024 data.

Table 1. Average dissolved oxygen and nutrient values between stations and between depths.

Between stations*	Oxygen (mg/L)	DIN (μM)	Phosphate (μM)	Silicate (μM)
North	5.81	25.61	2.22	45.57
South	5.41	27.09	2.32	46.03
Between depths*				
Surface	6.17	24.93	2.18	44.96
Bottom	4.79	28.51	2.38	47.20

* $p < 0.001$

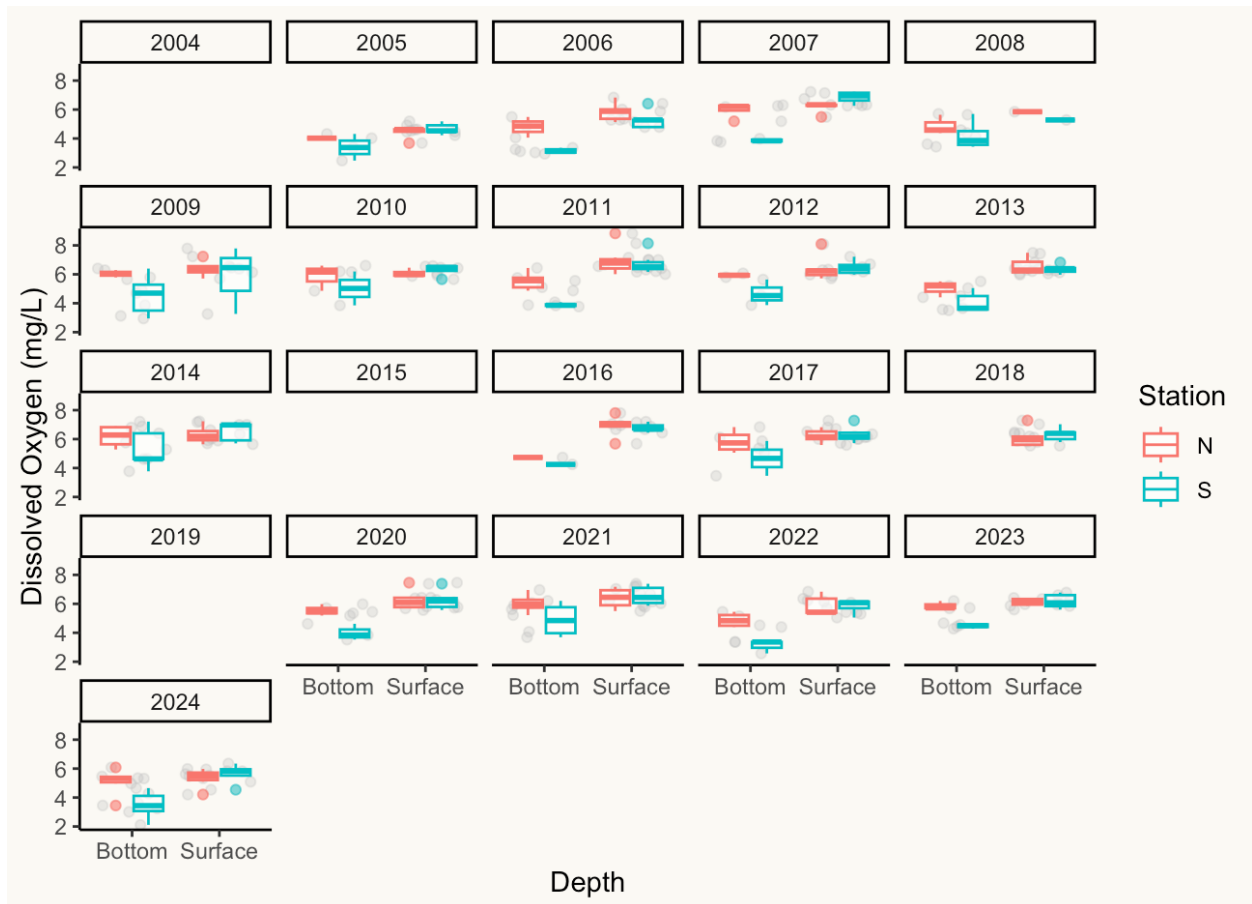


Figure 4. Interannual variability of dissolved oxygen (in milligrams per liter) at surface and bottom depths between North and South stations.

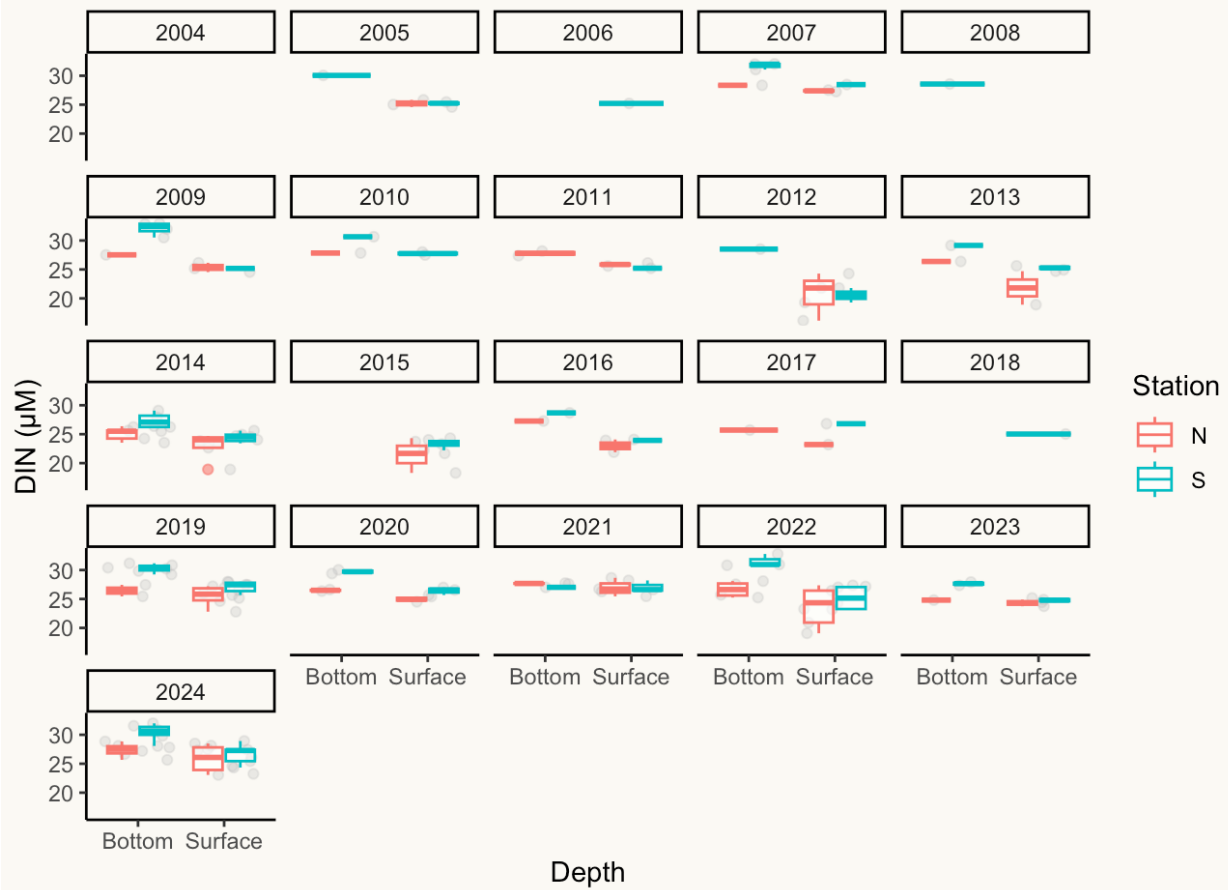


Figure 5. Interannual variability of dissolved inorganic nitrogen (DIN = sum of nitrate, nitrite, and ammonium concentrations) at surface and bottom depths between North and South stations.

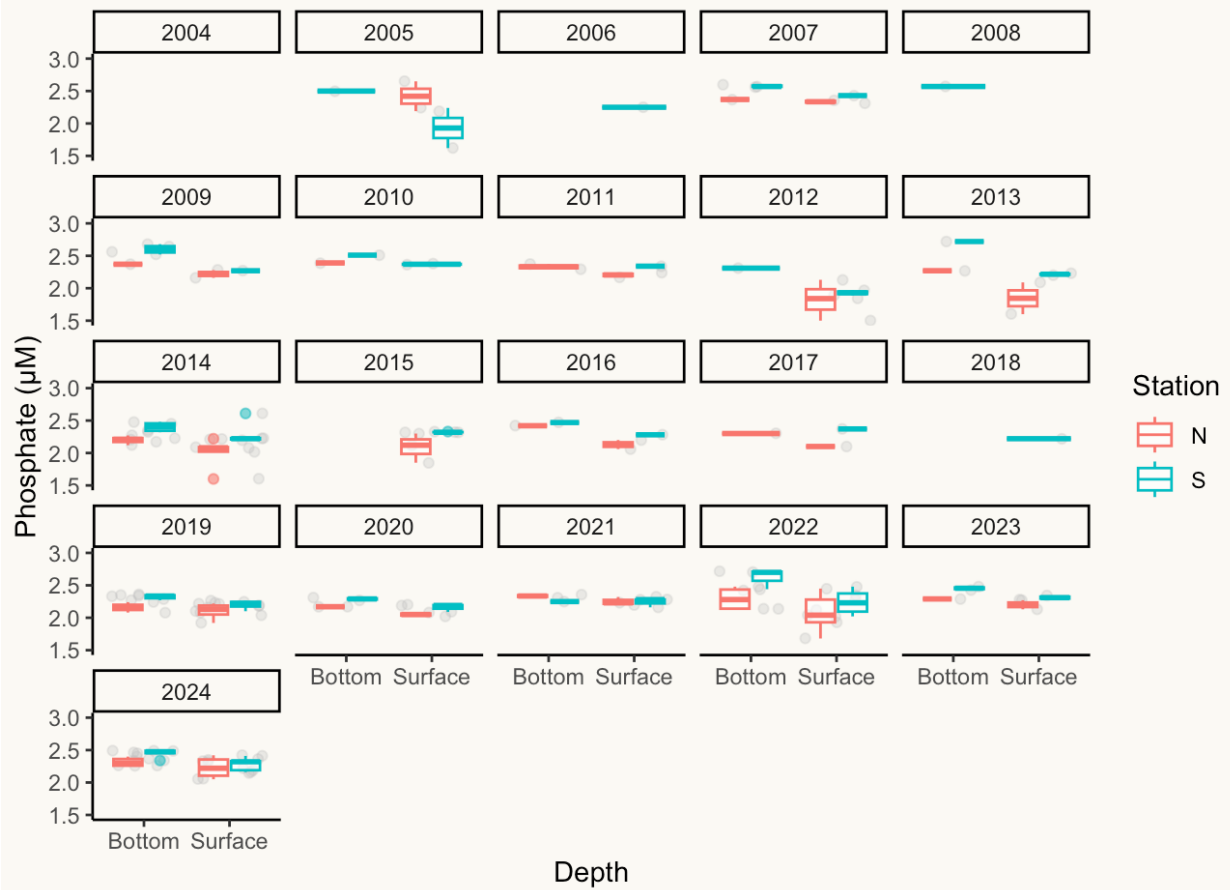


Figure 6. Interannual variability of phosphate concentrations at surface and bottom depths between North and South stations.

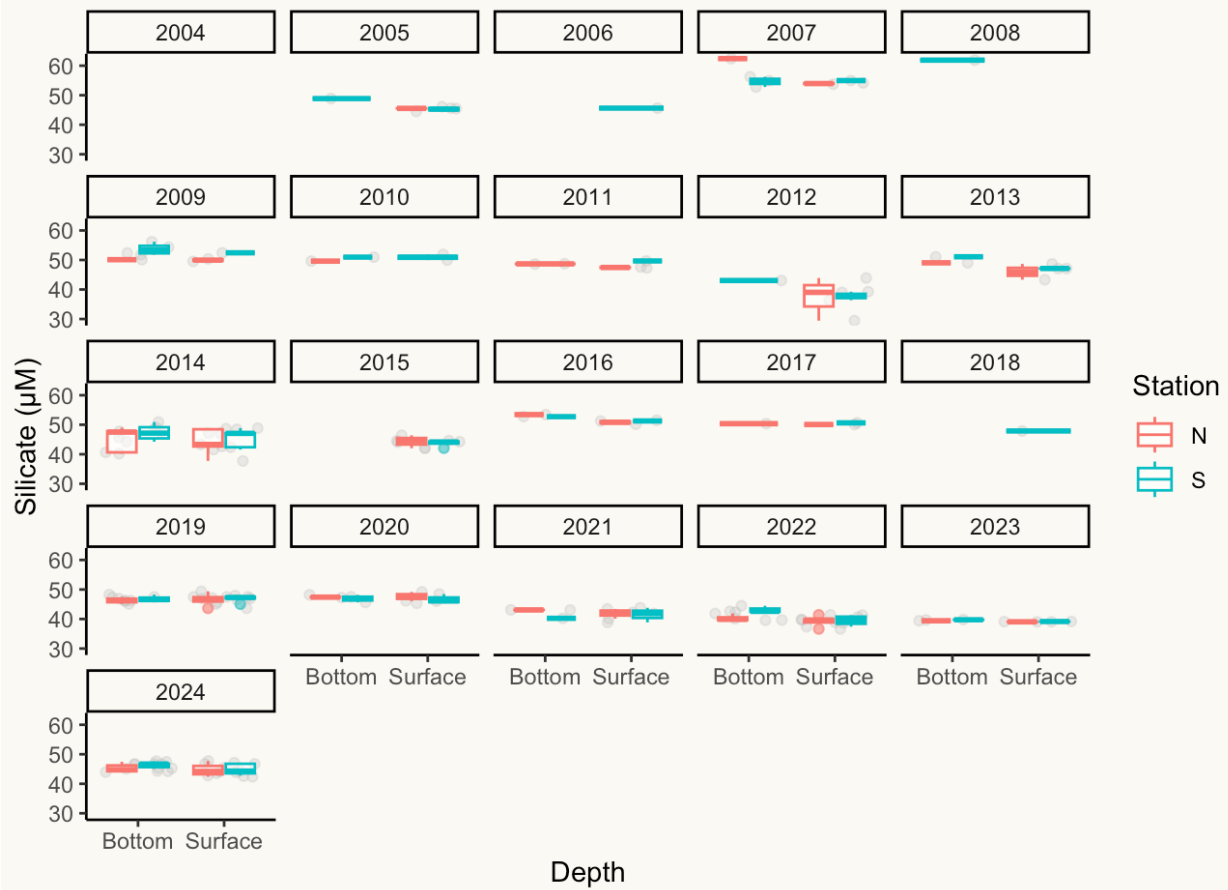


Figure 7. Interannual variability of silicate concentrations at surface and bottom depths between North and South stations.

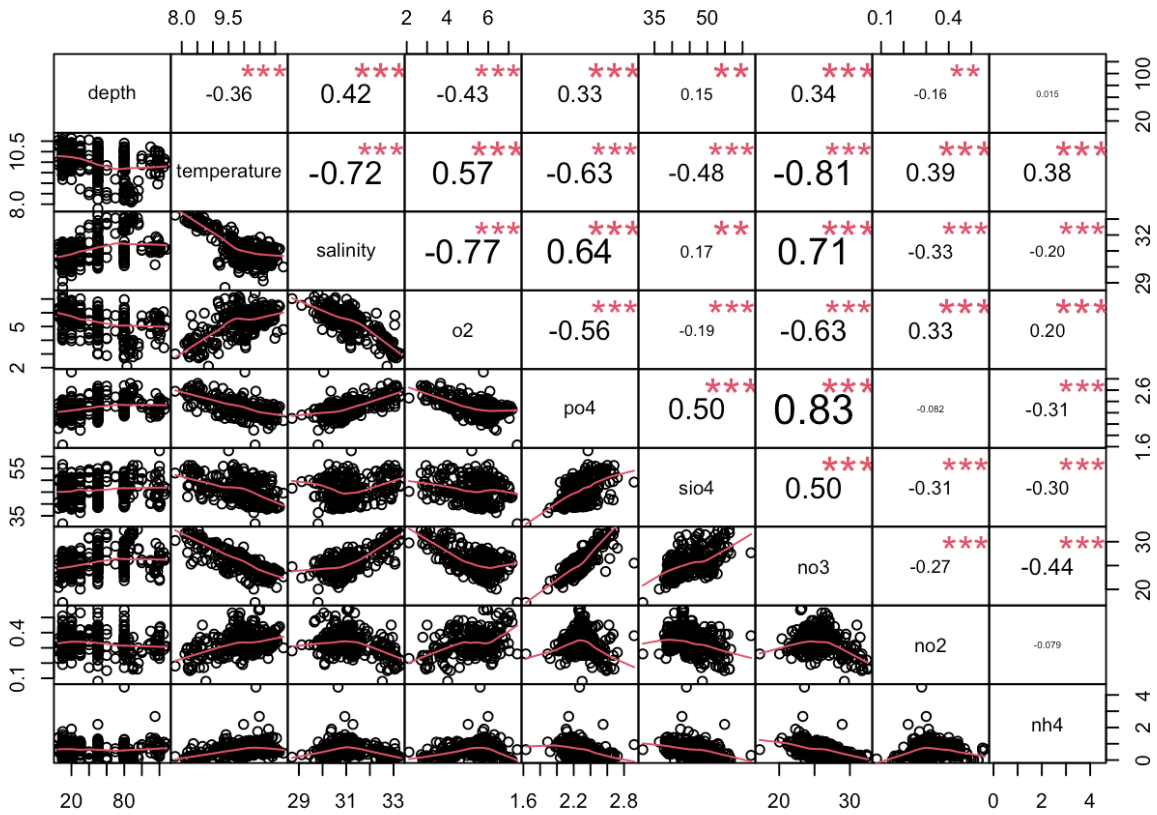


Figure 8. Multiple correlation analysis of physico-chemical parameters.

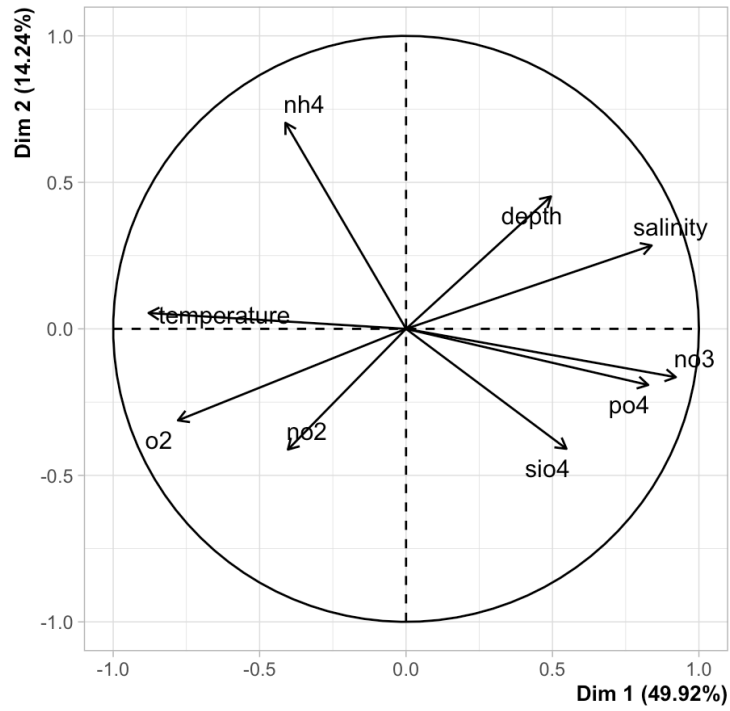


Figure 9. PCA variables

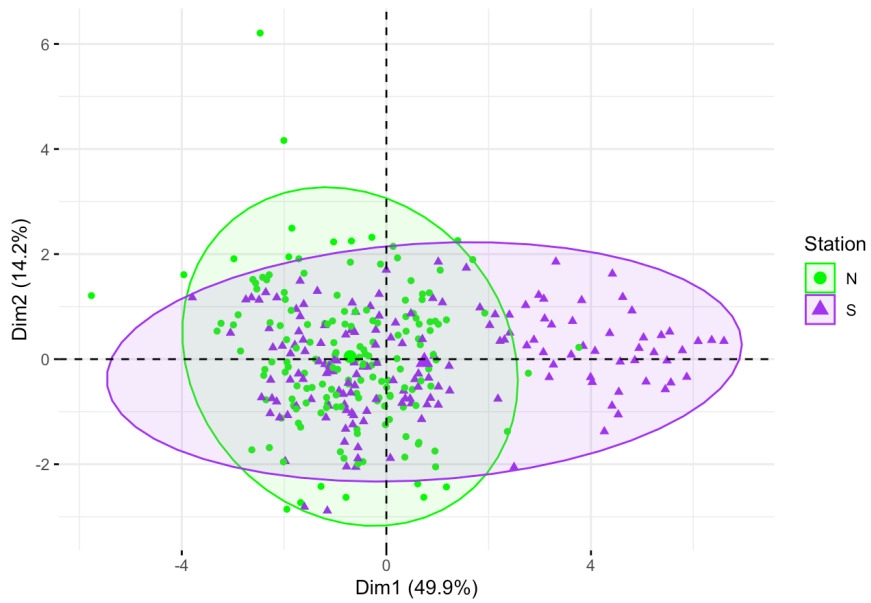


Figure 10. PCA plot showing the contribution of individual samples to principal components.

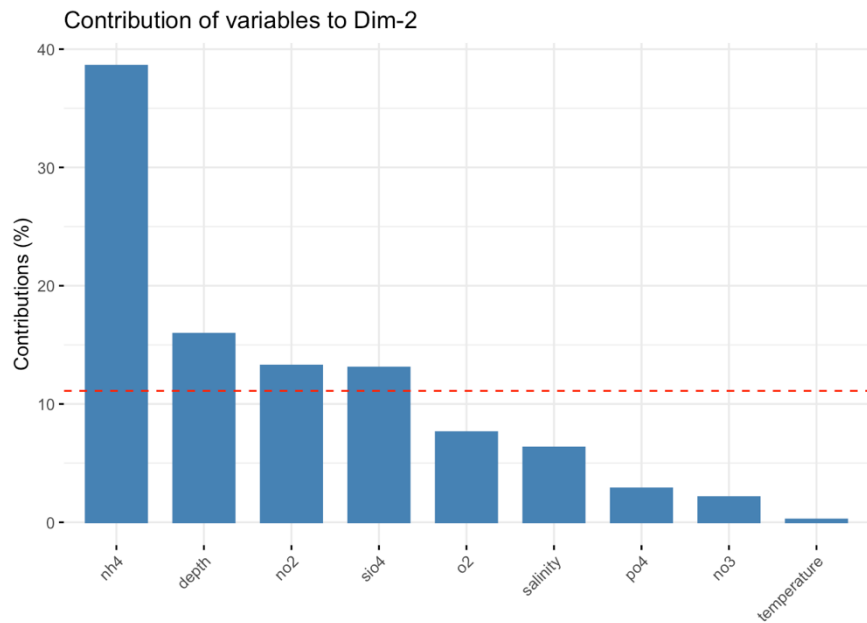
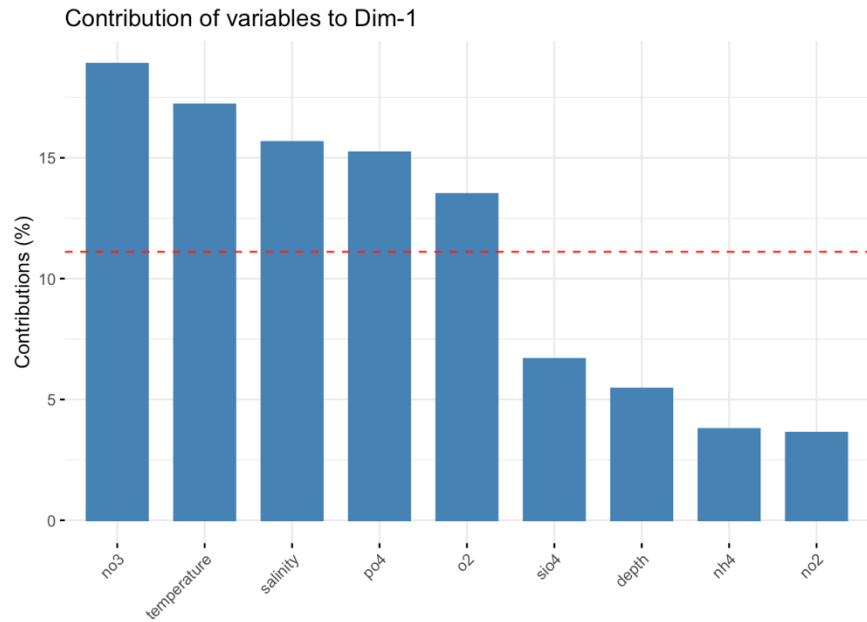


Figure 11. Proportion of contributions of each variable to the principal components.