Box Project 5.0

Investigating the status of Byfjorden

Uddevalla

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R/V Skagerak

GÖTEBORGS UNIVERSITET

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Abstract

Anoxic benthic conditions CAN precipitate algal blooms in Fjords and Estuaries (Stigebrandt et al. 2014), and they are a growing concern to the overall health of these marine environments. Mitigation of anoxic benthic habitats requires management of anthropogenic nutrient inputs (usually, agricultural runoff). However, this is not always possible. Water circulation in Fjords is often highly stratified and reliant on tidal or wind energy, or topography for mixing. Reducing strong stratification can help with preventing anoxic bottoms. An experimental design in Byfjorden has been attempting to mitigate anoxic benthic conditions by pumping oxygenated waters onto the bottom. Six years of continued testing shows no lasting impact from the experiment.

We were interested in the interactions of two water bodies; Havstensfjorden and Byfjorden. We sampled with a CTD, off the coast of Uddevalla in Byfjorden and Havstensfjorden. We found Havstenfjorden has oxygen present in the water column at depths down to 35m, whereas Byfjorden only reaches significant oxygen levels at 10 meters depth. This suggests Byfjorden is at a higher risk of anoxic benthic conditions than Havstenfjorden. We found a high level (3.9 mg/m^3) of fluorescence in Byfjorden, suggesting significant activity at 20 meters depth. We found a higher concentration of nutrients (Ammonium, Nitrate, Nitrogen dioxide, Phosphorus, and Silica) in Byfjorden. Nutrient concentrations were more consistent in Havstensfjorden, and deeper (although this may simply be a topographical difference).

Key Words: Anoxic Bottoms, Anoxic Benthic habitats, Fjord stratification, Oxygen mixing

Introduction and scientific objectives

The Baltic Sea has a long history of poor water quality and anoxic (oxygen depleted) benthic conditions. These anoxic conditions lead a series of chemical reactions that may result in large-scale cyanobacteria blooms (Stigebrandt et al. 2014).

As oxygen levels are depleted, anoxia leads to a reduction of metal ions in surface sediment. Phosphorus is then absorbed by metal oxide ions within the water column. As long as the water remains anoxic, phosphorus continues to leach from sediment, into the water column. This increase in phosphorus offsets the Redfield ratio- a phosphorous surplus results in a nitrogen deficit which leads to conditions that are more favourable for the growth of cyanobacteria, which can lead to several negative socioeconomic implications when present in a bloom (Stigebrandt et al. 2014).

One way of mitigating these poor water conditions is to decrease the external input of nutrients into coastal waters via the regulation of anthropogenic input (e.g. agricultural runoff). Another, more experimental method, of controlling these conditions is the direct oxygenation of bottom water by pumping oxygen rich surface water to the bottom. In the BOX project, the latter of the two methods was further tested within the confines of Byfjorden on the Swedish west coast (Stigebrandt et al. 2014).

Fjords are defined as glacially carved oceanic intrusions into land, they are deep and narrow with a shallow "sill" at the mouth and are characterized by estuarine water conditions. Due to their topography and proximity to land, fjords are often strongly stratified by high salinity (ocean-supplied) water and freshwater, from land input (Stigebrandt 2020). Water circulation is mostly driven by tidal changes, density differences, freshwater input, and wind-driven turbulence. Typically, fjords have three main layers of stratification; surface layer, intermediary, and basin water. The thickness of the intermediary layer is strongly dependent on sill depth and the denser (basin) water is trapped behind the sill (Stigebrandt 2020).

In recent years, continued focus of the BOX project has been placed on examining the status of Byfjorden, as well as the adjacent fjord; Havstensfjorden. Continued research over the past six years has shown no long-lasting effects from the BOX project on water column chemistry within Byfjorden (Stigebrandt 2020).

This year's project focused more specifically on interactions between the two fjords. Cruise specific objectives, aboard the R/V Skagerak, included CTD profiling of 14 sites chosen within By- and Havstensfjordens, collection and further nutrient analysis of 40 water samples, and box core sediment sampling. Sampling locations and sample collection depths were chosen by the team with the CTD profiles, observed in real time, and the following three research questions in mind:

1. *How does the water column hydrography (& nutrients) differ between the two fjords? Is there any evidence of water exchange over the sill?*
2. *Is there an observable difference in vertical stratification between the two fjords and if so, what implications does the stratification have on the water mass exchange between surface and deep water, and distribution of properties (e.g. nutrients)?*
3. *What is the distribution of dissolved oxygen and nutrients in depth and space; as well as between the two fjords and what can be said about the connection between dissolved oxygen and fjord health?*

Cruise overview

The study was performed at Byfjorden and Havstensfjorden, located just outside of Uddevalla. Our first plan was to sample eight stations in total; four stations in Byfjorden and four stations in Havstensfjorden. At these eight stations we conducted CTD profiling and collected water samples for later nutrient analysis. After sampling of the initial eight stations was concluded, we chose to use the remaining time available to move on to the sampling of additional sites that had been chosen prior to the cruise. These stations can be seen in Figure 1 and are shown as numbers 9-14. Additional nutrient samples were collected from stations 9 & 10 while CTD data was collected for every station. A sediment sample was also collected from station 14.

The choice of station locations was made by the team, based on specific properties of the two fjords. For example, we created a straight transect where the first station was just outside of Uddevalla harbour continuing out to the eighth station located in Havstensfjorden. We also chose to have one station from each of the fjords close to the sill (station 4 and 5). This because we wanted to see if there was any difference on either side of the sill or evidence of water exchange occurring between the two fjords.

In addition, we wanted to determine if there is a detectable difference between the deep parts of the two fjords. To help with make this determination, one station, from either side of the sill, was located in the deepest parts of the fjords. Some sites were also chosen to form a cross section that would sample perpendicular to the primary transect.

Cruise personnel

On Wednesday 23.9.2020, our research group went to Uddevalla for a one-day cruise to collect samples for our project. Samples from Byfjorden and Havstensfjorden were collected aboard R/V Skagerak. Participating in the cruise were; 7 students, 2 supervising researchers, and the ship's crew. Chiara Monforte was leader of our research group and organized sampling and communication between students and crew members. The rest of the students were divided into two groups; CTD operations and CTD profiling group. The groups switched their tasks halfway through the cruise. The CTD operations group was in charge of collecting water samples from Niskin bottles and preparing the CTD-rosette for the next sampling location. Whereas CTD profile group made the decision about depth of sampling, sample labelling and information writing. Because of restrictions due to COVID-19, students could not enter the main interior of the ship and communication with the ship's crew was mainly via one crew member and/or supervising researchers.

Table 1: Cruise personnel and positions.

Number	Name	Position
1	Ship's crew	Ship control, CTD manipulation
2	Sebastian Swart	Supervising researcher
3	Marcel du Plessis	Supervising researcher, CTD manipulation
4	Chiara Monforte	Communication and organization
5	Ellen Andersson	CTD operations and profiling
6	Felix Bravell	CTD operations and profiling
7	Shelby Joyce	CTD operations and profiling
8	Bela Klimesova	CTD operations and profiling
9	Mimmi Pettersson	CTD operations and profiling
10	Saga Stille	CTD operations and profiling

Diary and cruise narrative

The cruise began at 09.45 from Uddevalla, went through Byfjorden and Havstensfjorden, and concluded at 15.30 in Uddevalla. Weather was fair, with a light breeze and a day's high temperature of 18 °C.

The team broke into two groups and one of the smaller groups started with the CTD-profiling. Water samples from each site were collected at surface and bottom depths. The live results from the CTD monitor were observed and intermediate sampling depths were then chosen; based on the resulting variable profiles. The variables of interest were; Oxygen, Conductivity (salinity), Fluorescence, Temperature, and Pressure.

The other group started with the CTD-operations and water sampling. Several 15 ml falcon tubes were labelled with the number of the cruise day, the stations' number, and depth. Water was collected from the Niskin bottles into a 100 ml syringe with an attached filter to obtain samples for later nutrient analysis. Each sample was filtered into one of the labelled. The filter size used was 25 µm.

When half of the stations had been completed, the groups switched responsibilities so that everyone could obtain the same level of experience with both sampling and profiling. At least one person from the first group guided the second group when taking over, to ensure a smooth transition. The group members switched places during the day, as it became apparent that more people were required for water sampling operations than for profiling.

The ship's crew assisted constantly during the cruise, except for a lunch break at approximately 12.00. One problem occurred before starting the cruise. Initially, coordinates were not phrased according to the ship crews' preferences, but this was easily sorted out.

Station/Activities log

During the cruise, we sampled at a total of 14 stations. The first six stations were located along Byfjorden and into Havstensfjorden. After that, we sampled in Havstensfjorden; stations 7, 8, and 9 to cover the area of interest in the fjord and stations 10, 11, and 12 as a transect in Havstensfjorden. Lastly, stations 13 and 14 were done in order to obtain transect data across the innermost part of Byfjorden (Fig.1).

CTD profiling was conducted at every station, while water sampling (for nutrient analysis) was only conducted at stations 1-10. The number of samples varied between stations and was chosen based on station depth and CTD information about the water column. A box core was taken at station 14 in order to get a visual reference of benthic conditions at that station (Tab.2).

Station	Time (UTC+2)	Latitude	Longitude	Max depth (m)	Activity	No. of nutrient samples	Sample name and depth	Comments
1	10:20	58.34224	11.9013	15	CTD+water sampling	3	SK2S1Z1 (1m) SK2S1Z8 (8m) SK2S1Z15 (15m)	Inner Byfjord
2	10:48	58.3379	11.88676	38	CTD+water sampling	4	SK2S2Z1 (1m) SK2S2Z8 (8m) SK2S2Z18 (18m) SK2S2Z38 (38m)	Byfjord
3	11:08	58.3379	11.87008	45	CTD+water sampling	5	SK2S3Z1 (1m) SK2S3Z10 (10m) SK2S3Z15 (15m) SK2S3Z20 (20m) SK2S3Z45 (45m)	Byfjord
4	11:28	58.32908	11.8555	15	CTD+water sampling	3	SK2S4Z1 (1m) SK2S4Z11 (11m) SK2S4Z15 (15m)	Sill, Byfjord side
5	11:45	58.32376	11.8368	13	CTD+water sampling	3	SK2S5Z1 (1m) SK2S5Z8 (8m) SK2S5Z13 (13m)	Sill, Havstensfjord side
6	12:27	58.31921	11.81249	26	CTD+water sampling	4	SK2S6Z1 (1m) SK2S6Z9 (9m) SK2S6Z19 (19m) SK2S6Z26 (26m)	Havstensfjord
7	12:53	58.31888	11.78933	29	CTD+water sampling	5	SK2S7Z1 (1m) SK2S7Z9 (9m) SK2S7Z13 (13m) SK2S7Z22 (22m) SK2S7Z29 (29m)	Havstensfjord
8	13:11	58.30723	11.7924	35	CTD+water sampling	4	SK2S8Z1 (1m) SK2S8Z9 (9m) SK2S8Z23 (23m) SK2S8Z35 (35m)	Havstensfjord
9	13:30	58.31244	11.77377	38	CTD+water sampling	3	SK2S9Z1 (1m) SK2S9Z10 (10m) SK2S9Z38 (38m)	Havstensfjord
10	13:47	58.31632	11.7986	29	CTD+water sampling	6	SK2S10Z1 (1m), SK2S10Z9 (9m), SK2S10Z13 (13m) SK2S10Z18 (18m) SK2S10Z22 (22m) SK2S10Z29 (29m)	Havstensfjord
11	14:05	58.32104	11.79055	27	CTD	0		Havstensfjord
12	14:19	58.3114	11.80713	19	CTD	0		Havstensfjord
13	15:18	58.34492	11.89253	22	CTD	0		Inner Byfjord
14	15:01	58.33496	11.9048	21	CTD+Box core	0	Box core for visual of sediment	Inner Byfjord

Table 2: Stations log of cruise.

Cruise track charts

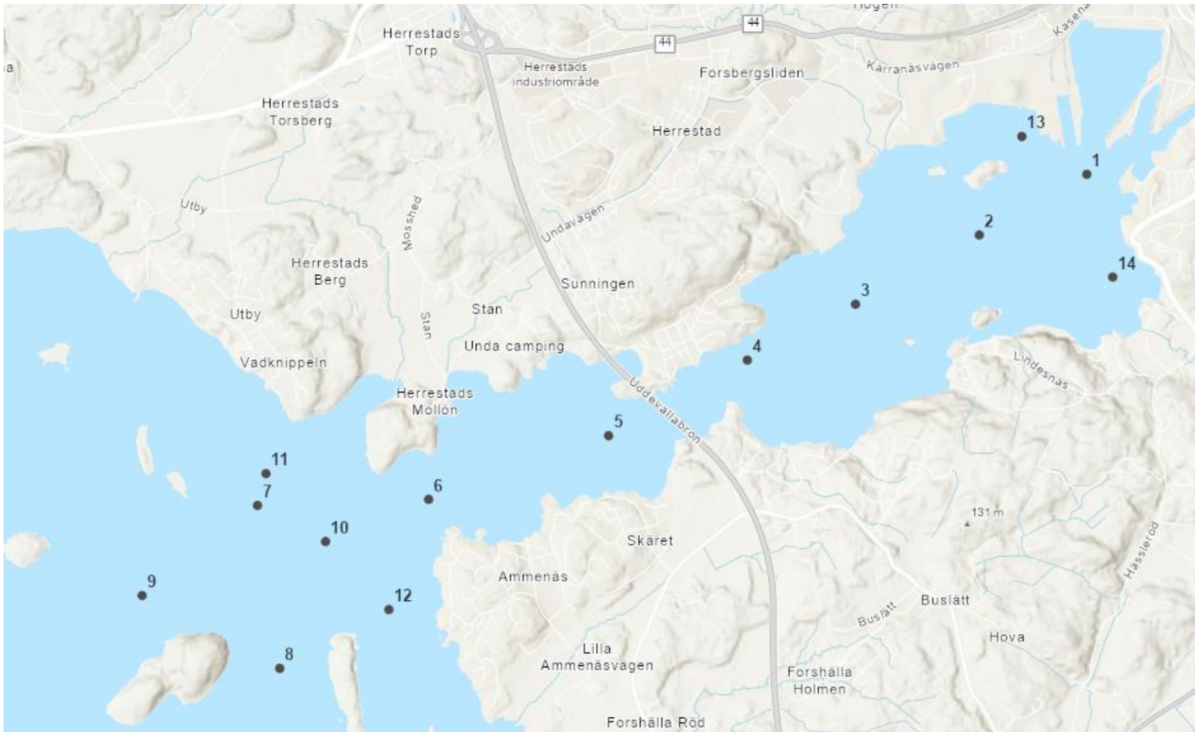

Figure 1: Map of Byfjorden region of the sampling area with station positions marked by numbers according to Tab. 2.

Results

In Byfjorden oxygen is close to 0 ml/l below 20 m depth. In both Havstensfjorden and Byfjorden surface oxygen values are around 6 ml/l. In both locations the main decrease in oxygen is around 10 m however, in Havstensfjorden it increases some at 10-25 m before it gets close to 0 ml/l around 35 m (Fig. 2). This means that Byfjorden bottom water is more anoxic than in Havstensfjorden.

If we were to calibrate oxygen, we would want to choose depths at which oxygen levels were stable; and if possible, we would sample from a range of depths. Looking at figure 2 (left), Byfjorden basically only has two different oxygen levels, so we would try to pick one of the deep stations in Havstensfjorden (Fig. 2 - right). Station 8 (purple line) has some stable sections at 0-10 m, 15-20 m and 30-35 m. We sampled at 9 m, 23 m, 35 m. The sample at 9 m could be used for calibration. However, to ensure stable oxygen levels, we could have taken samples at 5 m, 20 m and possibly one at 30 m; in addition to the bottom sample. We want to avoid calibration with values close to zero.

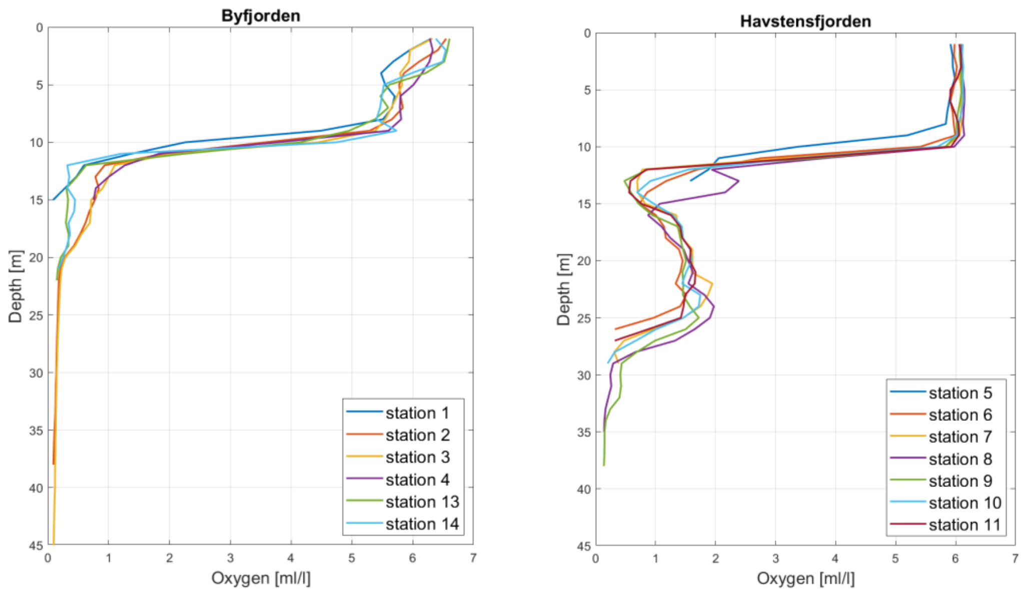

Figure 2: Oxygen concentration profile depending on depth in different stations in Byfjorden (left) and Havstensfjorden (right).

When chlorophyll reaches an excited state, it emits detectable energy in the form of fluorescence**.** This measurement can then be used as an indication of chlorophyll levels present within the water column. Byfjorden has fluorescence values between 2.5-3.5 mg/m^3 at the surface and gradually decreases to 1-0.5 mg/m^3 at 5m to 15 meters. The profile shows a deep chlorophyll maximum at 20 meters depth that spike up to almost 4 mg/m^3. Under 20 meters, fluorescence values are between 1-1.5 mg/m^3. Havstensfjorden has fluorescence values of 1-1.5 mg/m^3 between surface and 10 meters down. At 15 meters to the bottom, values drop to 0.5 mg/m^3 and below (Fig. 3). In general, surface chlorophyll is higher in Byfjorden than in Havstensfjorden. Byfjorden also has a chlorophyll maximum at 20 m.

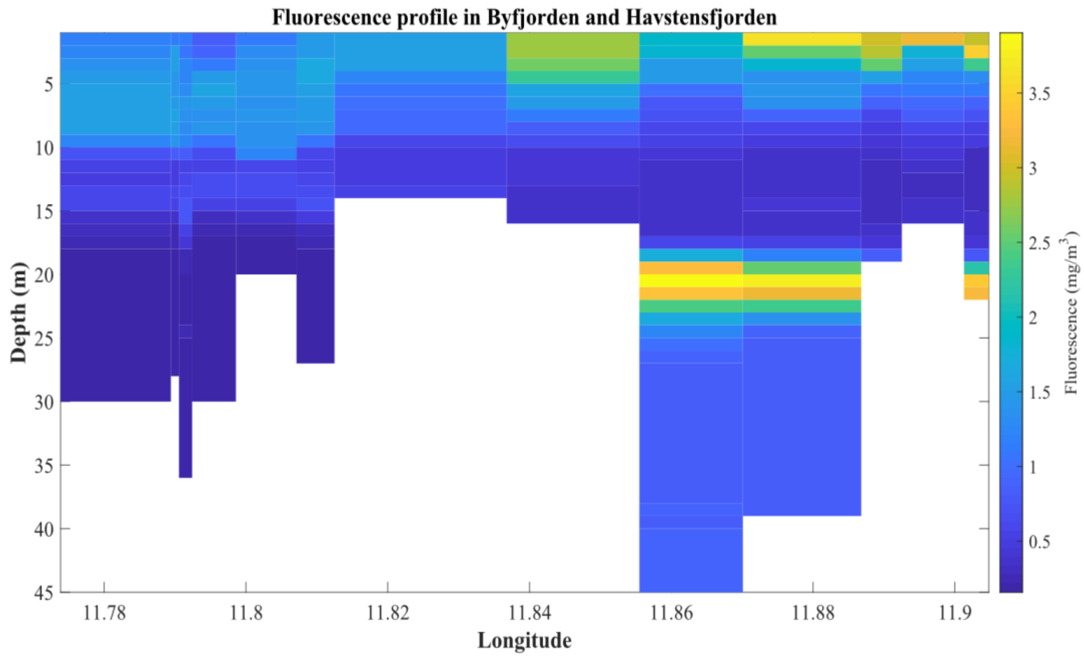

Figure 3: Fluorescence (mg/m^3) of Havstensfjorden (left) and Byfjorden (right). The sill dividing the fjords is positioned approximately at Longitude 11.82.

As we expected from previous studies, the practical salinity at surface level is 21±0.3 PSU at the innermost part of Byfjorden due to freshwater input. Salinity gradually increases outwards and reaches 22.8 PSU in Havstensfjorden (Fig. 4).

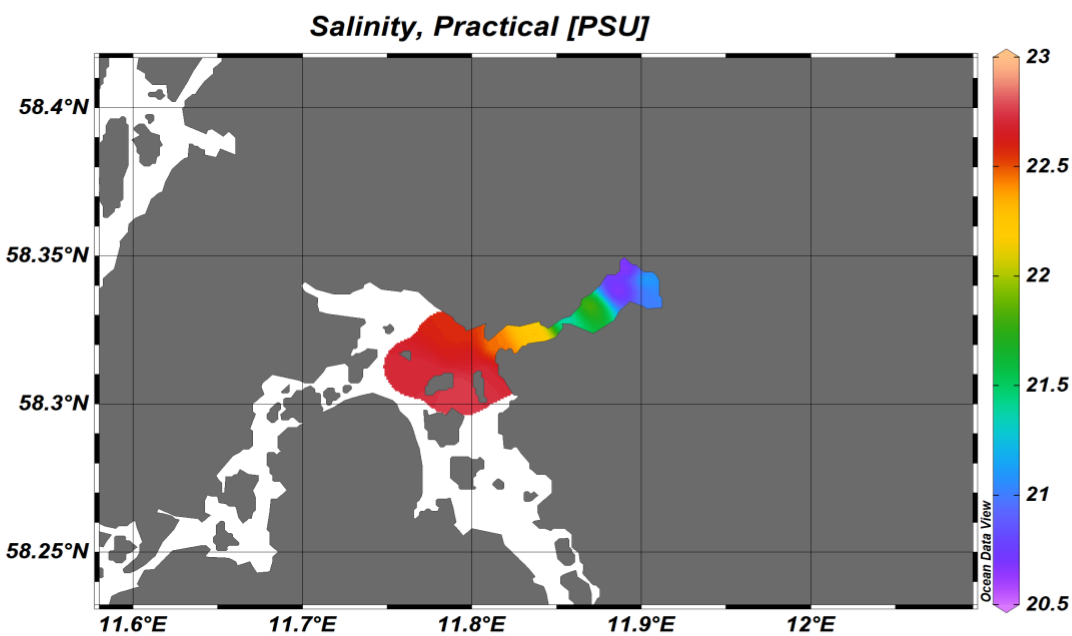

Figure 4: Surface salinity variation of the sampling area. Byfjorden is the area between colours purple/blue and orange (20.5-22 PSU) while Havstensfjorden is orange and red (22 PSU and above).

The NO_2 profile in Byfjorden is similar among all four stations. At station 2 and 3, high values (over 100 µmol/l) of NH_4 were observed towards the bottom while measurements at stations 1 and 4 were below 4 µmol/l. At stations 3 and 4 NO_3 concentration increases with depth down to 10m where it then starts to decrease. An opposite pattern can be observed at station 1. At station 2, NO_3 decreases with depth. The PO_4 and SiO_2 plots follow the same patterns as the NH_4 plot (Fig. 5). Both in Fig. 5 and 6, nutrients values below the level of detection have been assigned a value of “0” in the plots to make it easier to visualize.

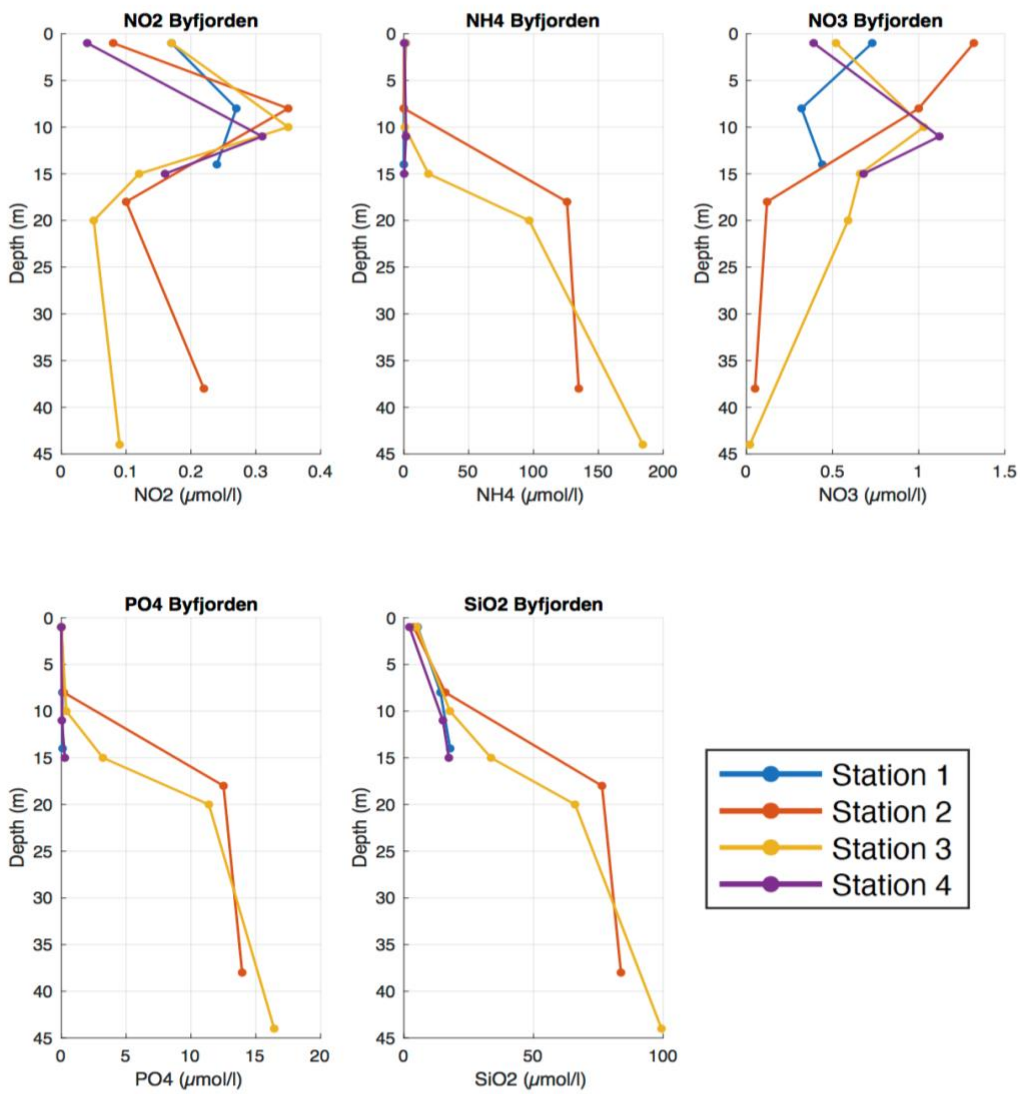

Figure 5: Variation of nutrients Nitrogen dioxide (NO_2), Ammonium (NH_4), Nitrate (NO_3), Phosphate (PO_4) and Silica (SiO_2) with depth in Byfjorden. Each station is represented by a colour and each sample is marked with a point in the graph.

The distribution of nutrient concentrations in Havstensfjorden is plotted in Fig. 6. NO_3, PO_4 and SiO_2 behave similarly to each other at all stations, low values were registered at the surface which increased with depth. At station 5, NH_4 shows a high concentration at the surface followed by a decrease with depth. At station 9 the concentration of NH_4 increases and peaks at the bottom. NO_2 values generally increase with depth at all stations with some exceptions.

In general, higher nutrient concentrations were observed in Byfjorden than in Havstensfjorden. However, in the case of NO_3, higher values were registered in Havstensfjorden (note different scale in figures). At both locations low values of nutrients were detected at the surface and their concentrations increased with depth.

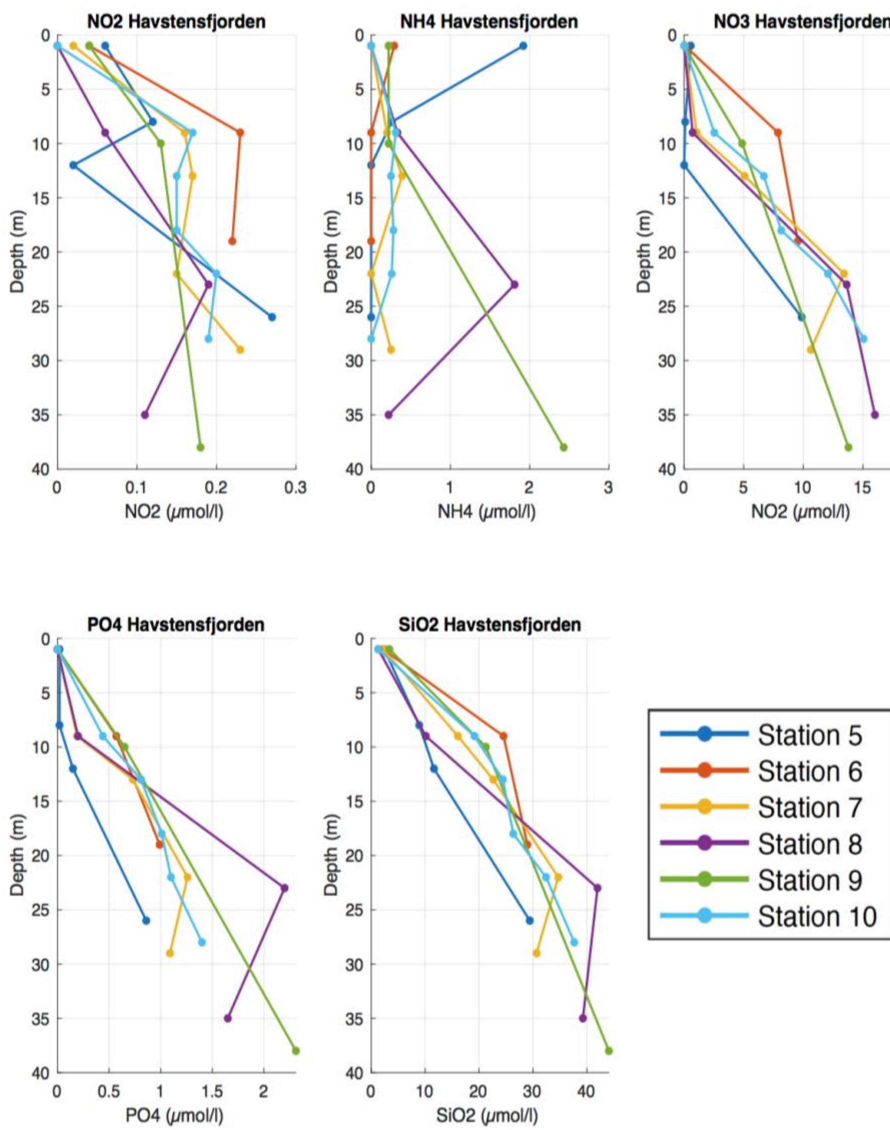

Figure 6: variation of nutrients Nitrogen dioxide (NO_2), Ammonium (NH_4), Nitrate (NO_3), Phosphate (PO_4) and Silica (SiO_2) with depth in Havstensfjorden. Each station is represented by a colour and each sample is marked with a point in the graph.

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