UNIVERSITY OF GOTHENBURG

INVESTIGATING THE STATUS OF BYFJORDEN AND HAVSSTENSFJORDEN WITH R/V SKAGERAK

Cruise report for MAR440
Date of cruise 2023-09-06

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Abstract

Byfjorden and Havsstenfjorden are two connecting fjords located in the archipelago of western Sweden. The conditions of these are very contrasting, with Byfjorden being more heavily stratified, with more anoxic conditions. The actual values of these conditions and how they compare to Havsstensfjorden were investigated by a cruise which covered comparable areas of both fjords. The measurements provided a deeper understanding of the hydrography and health of the fjords. Data was collected using a CTD-rosette equipped with Niskin bottles and a Box corer, which gave indicators of Byfjorden being more anoxic than Havsstensfjorden. Through smell and sight, both the water and sediment suggested divergent health between the two fjords, with Havsstensfjorden displaying healthier indicators than Byfjorden. The CTD casts that were done while collecting the water samples also supplied CTD profiles of the two fjords, showing that hypoxic and anoxic conditions appear more frequently in Byfjorden than in Havsstensfjorden.

Keywords: Fjord Health, Anoxia, Hydrography, CTD, Box Core, Byfjorden, Havsstenfjorden

Introduction and Scientific Objectives

Fjord circulation is affected by several factors such as weather, seasons, river input and anthropogenic impact. In turn, the circulation is limited due to a characterising sill located at the fjord mouth. Being located in between the open ocean and freshwater outflow, fjords are typically heavily stratified with distinct water masses (Stigebrandt, 2012). The oxygen concentration in partially enclosed basins, such as Byfjorden and Havsstensfjorden, is determined by the oxygen consumption rate, the frequency of complete mixing, and the oxygen concentration in the mixing water masses (Stigebrandt & Andersson, 2022).

Anthropogenic impacts have significantly increased nutrient input to coastal areas, causing eutrophication and fuelling plankton production and cyanobacteria blooms. The result is increased oxygen consumption, hence, oxygen depletion in the deeper waters. Anoxic conditions in the sediment cause a reduction of iron, releasing phosphorus and further fuelling the eutrophicated waters (Stigebrandt, 2015; 2022).

Byfjorden, located on the Swedish west coast, is characterised by heavy salt stratification due to its shallow entrance sill to the west, and freshwater input to the east. This results in weak water exchange between Byfjorden and the outer Havsstensfjorden, causing severe anoxia at the lower depths of the bay (Stigebrandt et al., 2015).

A BOX experiment was conducted in 2010-2012, in Byfjorden, where oxygenated surface water was pumped down into the sediment. The experiment successfully enhanced the conditions in terms of oxygenated deep water, the benthic community, and phosphorus retention (Stigebrandt et al., 2015). After the end of the BOX experiment, the enhanced parameters were reset and continuous monitoring of the area has been conducted since.

The aim of this cruise was to investigate the hydrography of Byfjorden and Havsstensfjorden and to assess the state of the fjord system by using water samples, grab samples and high-resolution CTD profiles of oxygen, salinity, temperature and fluorescence. Fluorescence profiles will be used to aid the investigation of the unidentified layer of fluorescence located below the Byfjorden's sill.

Cruise Overview and Methodology

Table 1. An overview summarising the brand and specifics of each scientific instrument that was used for sampling during the cruise.

Scientific instruments	Model
CTD	Seabird SBE 911, including turbidity, fluorescence, transmission, oxygen and PAR
Rosette system	SBE 32, 24 Niskin bottles (8 litres)
ADCP (mounted)	RDI; 150/600 kHz
Weather station	Aanderaa AWS 2700
Multibeam echo-sounder	EM2040 Kongsberg
Sub-bottom profile	TOPAS Kongsberg
Acoustic positioning system	HIPAP Kongsberg
Sediment grabber	Box corer

Field Methodology

For this cruise, the vertical CTD profile transect method was used to understand the status and determine the overall health of Byfjorden and Havsstensfjorden. The collected CTD data allowed for the detection of changes in chemical and physical properties in two dimensions. The first focuses on the vertical profile in the water column, the second dimension being a transect throughout both fjords.

Given the diverse framework conditions and unique bathymetry of the fjords (e.g., a significant sill, a harbour and outflowing river in Byfjorden, as well as a shallow seabed in Havsstensfjorden), a particular focus was placed on their comparison. Hence, most of the stations were chosen accordingly to capture the different CTD profiles of the fjords as thoroughly as possible.

In total, 15 stations were visited with one CTD cast each. The first five stations were located in Byfjorden, reaching from the river inlet to the sill. The remaining ten stations were chosen to be in the Havsstensfjorden. Seven going from the sill to the northernmost point, one at the deepest point, comparing both fjords at an approximately equal depth, and the last two were cast further south at the east and west end of the island Brattön, enabling the detection of potential southern water inflow from R/V Skagerak. The stations were chosen to cover various depths throughout both fjords (***Figure 1***).

For learning purposes, water samples were spontaneously collected using Niskin Bottles on the CTD-rosette. As the crew took turns monitoring the CTD, each new group tried to collect water samples from interesting depths. Each student took turns collecting water from the Niskin bottles. These water samples were analysed with a smell test.

Additionally, a box-corer was deployed two times, once in each fjord, to compare the appearance and composition of the two fjords' sediments.

Moreover, the cruise served as a learning experience to familiarise ourselves with operating a CTD, planning a research expedition, communicating amongst ourselves and the personnel, and adapting to unexpected changes.

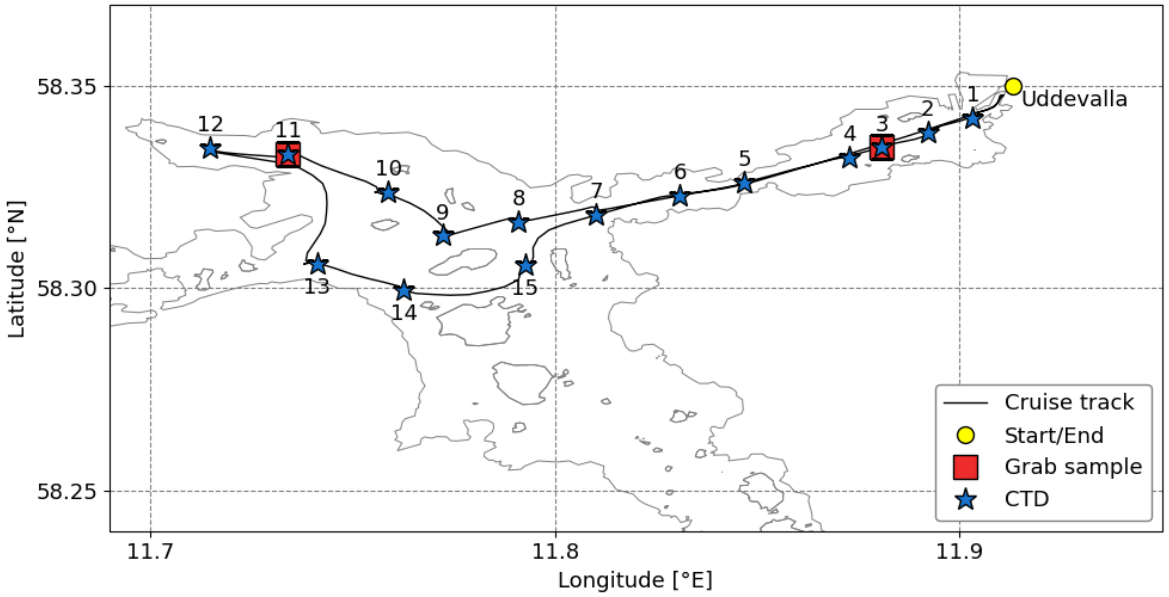

Figure 1. *Map of the survey area with the cruise track (black line), conducted CTD casts (blue stars) and grab samples (red boxes).*

Data Analysis Methodology

All collected CTD data were re-gridded at a vertical resolution of 0.1 m. Temperature and salinity values measured with the CTD were calculated to conservative temperature and absolute salinity in Python using Gibbs SeaWater (GSW) Oceanographic Tool Box. Conservative temperature and absolute salinity provide a better representation of the whole water column, as these parameters are affected by depth (Pawlowicz, 2013).

The water density was then calculated using temperature, salinity, and depth. The Mixed Layer Depth (MLD) were computed using a standard density threshold method, using the following formula:

$$MLD = \rho_{z5} - \rho_{z_i} \geq 0.03 \text{ kgm}^{-3}.$$

The formula computes the difference between the reference density, ρ, at 5 metres, and the density values for each CTD profile at all depths, z. The location of the MLD was found where the difference was equal or greater to the chosen threshold value (0.03 kgm^{-3}).

Diary Narrative

Once the group embarked on the R/V Skagerak, they were provided with a brief overview of the ship's main safety and commodity features, followed by a short explanation of the major capabilities of the CTD-rosette system before departing around 10:00 am. Sampling was conducted from 10:17 am to 15:18 pm, by rotating groups of three members. In total, 15 stations were visited, seven involving water sample collection and two utilising box corer deployment (***Table 2***). Around 15:45 pm the group was returned to Uddevalla's harbour, with a briefing on the outcomes and subsequent handling of the data taking place before the eventual group's departure.

Despite a cloudy morning, the temperature increased from 15.8 °C to 16.9 °C closer to the midpoint of the cruise, and the weather remained relatively calm throughout the day. The water surface maintained a tranquil state throughout the journey whilst remaining unaffected by a change in wind speed, which occurred from the minimal observed range of 1.2 - 2.3 m/s at the beginning of the day, gradually increasing to an average of 3.55 m/s, with occasional gusts exceeding 9.8 m/s in the afternoon.

The air temperature stabilised around 18 °C closer to the last hours of the cruise, accompanied by a clear sky. The stability is likely the result of the traceable increase in air pressure, which ranged from 1023 hPa at the start to 1024 hPa closer to the end of the voyage.

Several problems occurred during the journey, the majority stemming from hardware-based issues. While conducting CTD measurements at the initial station around 10:17 am, a minor malfunction of the pump affected the proper water sampling during the ascent of the CTD-rosette's apparatus, resulting in only the descent data being available for that cast. An additional complication took place shortly afterwards, upon the arrival of the vessel to station four at approximately 11:35 am. The deployment of the rosette sampler from the ship was prevented by an accidental uncontrolled lift of the CTD while still on the deck. The vessel's crew identified that there was some deformation to the CTD-rosette's winch system. However, after the crew had tinkered, it operated properly until the end of the cruise.

Station/activities log

Table 2. *A summary of station data, including activities, location and time of visit. Bot is an abbreviation for bottle.*

Station name	Date, YY-MM-DD	Longitude	Latitude	Start - End, Time CET	Event Description	Depth, m	Activity Identifier	Comments
01	23-09-06	58°30.523'N	11°54.196'E	10:12-10:14	6 bottles fired	10.9	CTD, Niskin bottles	Pump error - measurements taken only on the way down.
02	23-09-06	58°20.314'N	11°53.524'E	10:32-10:33		35.8	CTD	Strong bottom current. No oxygen below 20m.
03	23-09-06	58°20.088'N	11°52.840'E	10:51-10:52	Bot 1: 43.8m, Bot 2: 19,8m, Bot 3: 5,1m	43.8	CTD, Niskin bottles, Box core	
04	23-09-06	58°19.931'N	11°52.240'E	11:20-11:34	Bot 1: 45m, Bot 2: 42,7m, Bot 3: 19,8m, Bot 4: 1,9m	45	CTD, Niskin bottles	Malfunction of the CTD before measurements.
05	23-09-06	58°19.572'N	11°50.807'E	11:53-11:56		12.4	CTD	
06	23-09-06	58°19.373'N	11°49.790'E	15:17-15:17		16.7	CTD	The station was measured on the way back to the port.
07	23-09-06	58°19.140'N	11°48.607'E	12:12-12:15		26	CTD	
08	23-09-06	58°18.988'N	11°47.459'E	12:23-12:29	Bot 1, 2: 25m, Bot 3: 15m	30.8	CTD, Niskin bottles	
09	23-09-06	58°18.776'N	11°46.393'E	12:36-12:47	Bot 1: 38m	38.1	CTD, Niskin bottles	
10	23-09-06	58°19.424'N	11°45.331'E	12:52-13:05		12.7	CTD	
11	23-09-06	58°19.992'N	11°44.045'E	13:10-13:23	Bot 1: 16,8m, Bot 2: 10m	16.8	CTD, Niskin bottles, Box core	
12	23-09-06	58°20.035'N	11°42.892'E	13:45-13:49		11.5	CTD	
13	23-09-06	58°18.356'N	11°44.280'E	14:11-14:17	Bot 1,2: 39m, Bot 3: 20m, Bot 4: 5m	39.1	CTD, Niskin bottles	
14	23-09-06	58°17.975'N	11°45.763'E	12:33-12:35		21.2	CTD	
15	23-09-06	58°18.340'N	11°47.563'E	12:40-12:54		36.5	CTD	

Preliminary Results

CTD Data

In total, data from 15 CTD casts were obtained. The collected data on temperature, salinity, density, fluorescence and oxygen, is presented in ***Figure 2***. The results of conservative temperature indicate a decrease in temperature with depth. Furthermore, the CTD-casts of stations 6-12 show lower temperatures in shallower depths. Absolute salinity plots show higher salinity with depth. The density, which is dependent on temperature, salinity and depth (Pawlowicz, 2013), follows previous trends and increases with depth. The fluorescence decreases with depth, although station 2, 3 and 4 seems to have another peak at around 20 m depth. The oxygen decreases rapidly with depth reaching hypoxic and anoxic levels at the basins of the fjords.

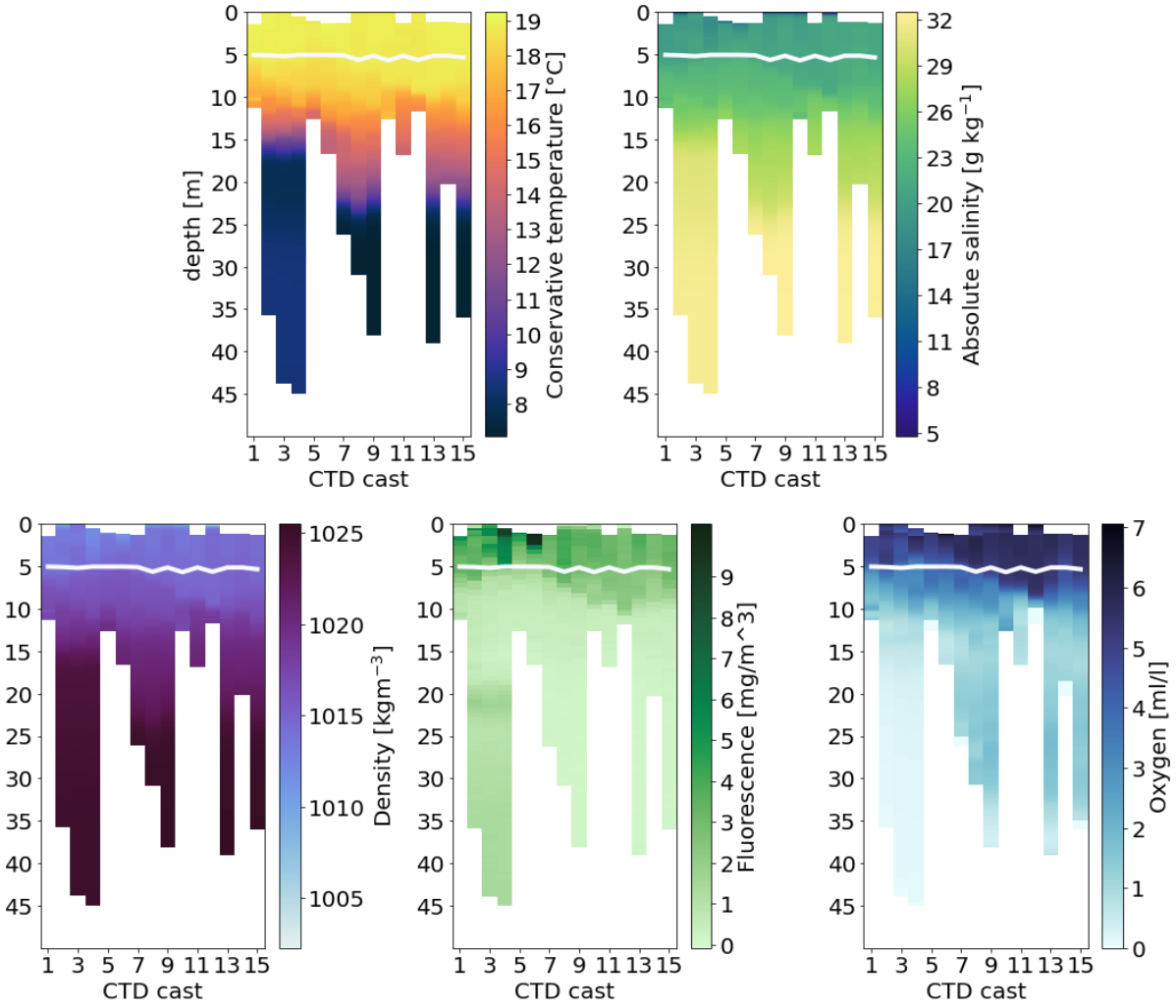

Figure 2. *Plots showing CTD sampling results of conservative temperature (top left) absolute salinity (top right) and water density (bottom left), fluorescence (bottom middle) and oxygen (bottom right) of all 15 sampling stations. The white line represents the Mixed Layer Depth (MLD).*

Meteorological Data Results

Meteorological data was collected continuously throughout the cruise, presented in ***Figure 3*** and ***Figure 4***. The air temperature increased during the day with a minimum of 15.5 °C and a maximum of 18.6 °C. The opposite pattern could be observed in the relative humidity data with a maximum of 88% and a minimum of 73%. The air pressure was relatively stable with a maximum of 1024 hPa and a minimum of 1023 hPa (***Figure 3***).

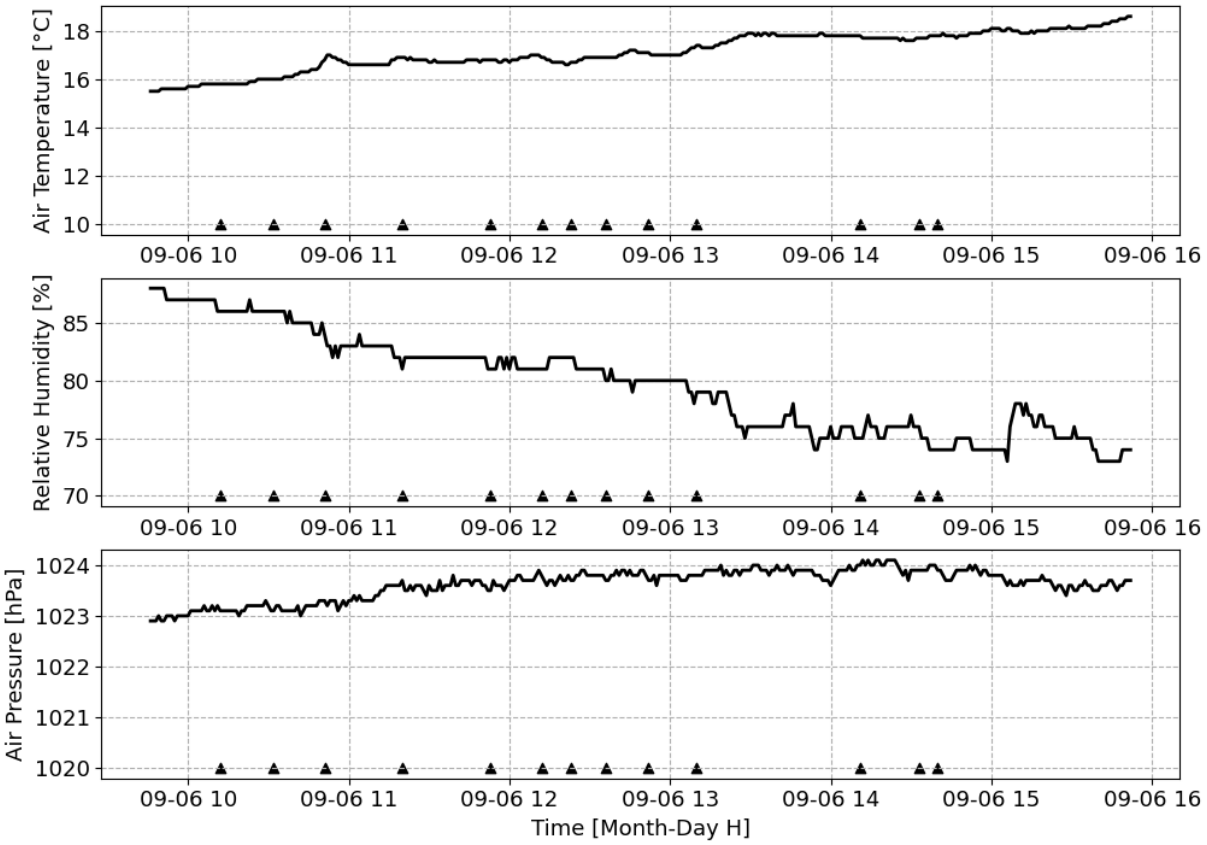

Figure 3. *Plots showing MET data of air temperature (top), relative humidity (middle) and air temperature (bottom) throughout the day. Conducted CTD casts are marked with black triangles.*

As seen in ***Figure 4***, the wind speed was between 2.2 ms^{-1} and 4.1 ms^{-1} in a southwest direction for 12 % of the cruise time. Stronger winds (~ 2.2 ms^{-1} - 9.8 ms^{-1}) were blowing to the north and northeast direction for around 20% of the journey time. The fastest wind (>9.8ms^{-1}) was recorded blowing to the northwest, however, for a short period of time (<1%). Overall, during the journey winds were predominantly blowing to the north, northeast and northwest directions for the majority of the time.

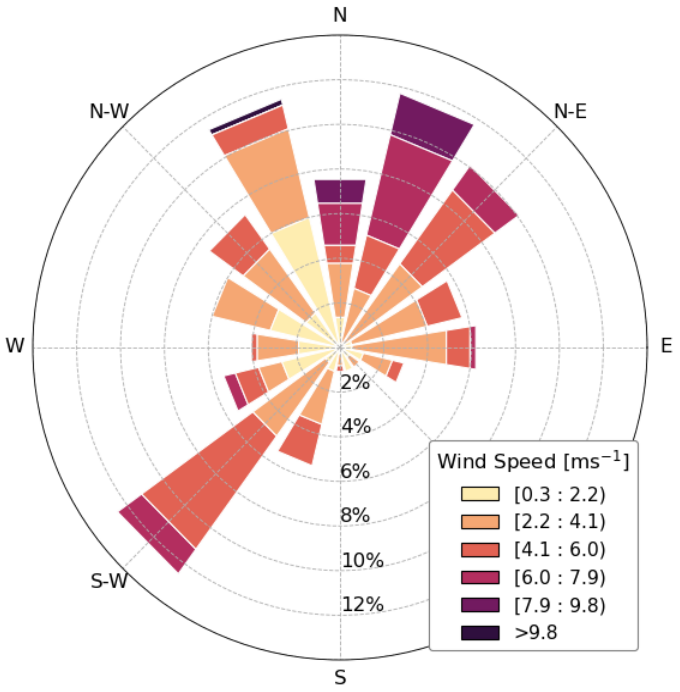

Figure 4. *Plot showing MET data of wind direction and wind speed during the cruise.*

Ferry Box Results

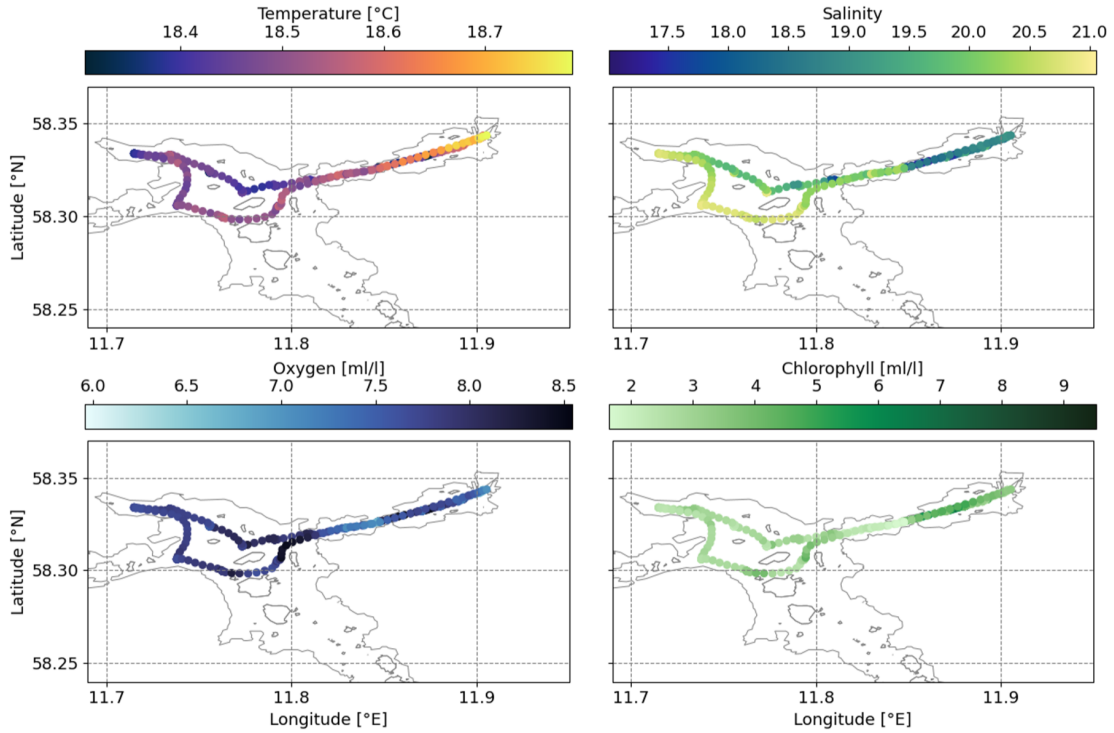

Figure 5. *Maps showing ferry box data of a) temperature, b) salinity, c) oxygen, and d) chlorophyll from the 3 m deep seawater intake on R/R Skagerak. Data was collected every minute for the duration of the cruise (2023-09-06, 10:02 to 15:44).*

Ferrybox data of temperature, salinity, oxygen, chlorophyll, CDOM, pH, turbidity, and phycocyanin was measured continuously at 1 min. intervals from the 3 m deep seawater intake onboard. ***Figure 5*** shows temperature, salinity, oxygen and chlorophyll measured during the duration of the cruise. The

highest values of temperature were found in Byfjorden, increasing towards the river outlet (***Figure 5 a***). However, this could be due to an increase in atmospheric temperature rather than riverine impact, as a similar increase in air temperature can be seen in ***Figure 3***. Salinity increased from ~18.5 at Byfjorden's furthest point, to ~20.5 maximum in Havsstensfjorden (***Figure 5 b***). The highest values of oxygen (8-8.5 ml/l) were found in Havsstensfjorden just before the sill into Byfjorden (***Figure 5 c***), while the maximum chlorophyll values were found in Byfjorden (4-5 ml/l) (***Figure 5 d***).

Grab Samples

The two grab core samples were obtained successfully with a box corer. Images of the sediment are visualised in ***Figure 6*** and ***Figure 7***, results from the examination of the sediment are summarised in ***Table 3***.

Both Box Core Samples consisted of soft and smooth clay, sample 06/BOX/3 had a lighter grey colour and a strong sulphur smell. Sample 06/BOX/11 had a darker grey colour and a mild sulphur smell. No fauna were found in 06/BOX/3. Two *Littorina littorea* shells and one *Cerastoderma edule* shell were found in sample 06/BOX/11, however, no live organisms were visible to the eye.

Figure 6. *Sample BOX/3*

Figure 7. *Sample BOX/11*

Table 3. *Summation of box core sample features.*

Measurement	BOX/3	BOX/11
Grain Size	Soft clay	Soft clay
Colour	Light grey	Dark grey
Smell	Strong sulphur smell	Mild sulphur smell
Fauna	None	Bivalve shells

Water Samples

The smell tests revealed a distinct difference between water samples from Byfjorden and Havsstensfjorden. Most water samples from Byfjorden exhibited a strong to mild smell throughout the water column, however, the upper five metres had no smell. All water samples from Havsstensfjorden had no smell. A detailed description of the water samples is presented in ***Table 4***.

Table 4. *Results of CTD water sample smell-test.*

Site ID	Depth	Smell
CTD/3	~ 5 m	None
	~ 20 m	Mild
	~ 44 m	Strong
CTD/4	~ 2 m	Weak
	~ 20 m	Mild
	~ 43 m	-
	~ 45 m	Strong
CTD/8	~ 15 m	None
	~25 m	None
CTD/9	~38 m	None
CTD/11	~ 10 m	None
	~ 17 m	None
CTD/13	~ 5 m	None
	~ 20 m	None
	~ 39 m	None

Acknowledgements

We offer our utmost gratitude to the crew working during our cruise day on R/V Skagerak. It was a luxury to observe the crew working and learning while also being able to participate in various activities necessary for our sampling. We would also like to thank the chef on board for making us a wonderful lunch.

Furthermore, we would like to extend our appreciation to Johan Edholm and Marcel Du Plessis for supervising us throughout the day and being our rocks in the non-existent storm.

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