Monitoring ocean acidification in Norwegian seas in 2021 – selected results

Made by the Institute of Marine Research, NORCE Norwegian Research Centre, Norwegian Institute for Water Research, and University of Bergen

Monitoring Report

M-2311 | 2022

Colophon

Executive institution

Institute of Marine Research, NORCE Norwegian Research Centre, Norwegian Institute for Water Research, University of Bergen

Project manager for the contractor

Melissa Chierici

Contact person in the Norwegian Environment Agency

Gunnar Skotte

M-no	Year	Pages	Contract number
2311	2022	36	17078007

Publisher

Norwegian Environment Agency

The project is funded by

Norwegian Environment Agency

Author(s)

Jones, E., I. Skjelvan, H. Frigstad, M. Chierici, H.H. Lødemel, T. Kutti, A.L. King, A. Omar, G. Christensen, S. Marty, E. Protsenko, C. Mengeot, L. Valestrand, P. F. Jaccard, K. Jackson-Misje, T. de Lange, M. Becker, C. Mourgues

Title – Norwegian and English

Monitoring ocean acidification in Norwegian seas in 2021 – selected results / Havforsuringsovervåking i norske farvann i 2021 – utvalgte resultater

Summary – sammendrag

This is the 2021 annual report from the program: 'Monitoring ocean acidification in Norwegian waters' funded by the Norwegian Environment Agency. The measurements are performed by the Institute of Marine Research, NORCE Norwegian Research Centre, Norwegian Institute for Water Research, University of Bergen, and Akvaplan-niva. The measurements are collected in coastal waters as well as in open ocean and are from the Skagerrak, the Norwegian Sea, and the seasonally ice-covered Barents Sea. This report presents selected data from 2021.

Denne årsrapporten for 2021 presenterer undersøkelser fra programmene 'Overvåkning av havforsuring i norske farvann' utført av Havforskningsinstituttet, NORCE Norwegian Research Centre, Norsk institutt for vannforskning, Universitetet i Bergen og Akvaplan-niva på oppdrag fra Miljødirektoratet. Målingene er gjort i kystvann og i åpent hav, og områder som er undersøkt er Skagerrak, Norskehavet og deler av Barentshavet. Rapporten presenterer utvalgte data fra 2021.

4 emneord	**4 subject words**
Havforsuring, karbonatsystem, mellomårlig- og sesongsvariasjon, biogeokjemiske prosesser	Ocean acidification, carbonate system, interannual and seasonal variability, biogeochemical processes

Front page photo

E Jones, IMR

Contents

1. Summary

1.1 English summary

This is the annual report for 2021 of the programs ‘Monitoring ocean acidification in Norwegian waters’ funded by the Norwegian Environment Agency. The first program started in 2013 and has consisted of the following partners: Institute of Marine Research (IMR), NORCE Norwegian Research Centre (NORCE), Norwegian Institute for Water Research (NIVA), and University of Bergen (UiB). The latter program started in 2019 with the following partners: IMR, NORCE, NIVA, and Akvaplan-niva (ApN). The results presented are based on measurements of Total Alkalinity (A_T), Dissolved Inorganic Carbon (C_T), partial pressure of CO_2 (pCO_2), and pH made in open and coastal waters, in surface water and over the full water column, and by discrete sampling and continuous measurements. In this report, the focus has been on new activities started in 2021, and on results from continuous measurements.

1.2 Norwegian summary

Denne årsrapporten for 2021 beskriver utvalgte resultater fra programmet “Overvåking av havforsuring i norske farvann”. Målet med prosjektene har vært å øke kunnskapen om havforsuring i norske havområder inkludert kysten, og dette omfatter status for havforsuring, hvordan dette naturlig varierer mellom områder og årstider og hvordan havforsuring utvikles over år. I denne rapporten er fokus på nye aktiviteter som startet i 2021 og på resultater fra kontinuerlige målinger.

2. Introduction

The Ocean Acidification Monitoring program was started in 2013 by the Norwegian Environment Agency, and in 2019, a supplementary monitoring program - Ocean Acidification of Coastal Waters - was initiated. These initiatives were based on a need for increased knowledge on how and at which speed the ocean responds to the constantly increasing content of atmospheric carbon dioxide (CO_2). Results from the programs so far have been presented in Chierici et al. (2014; 2015; 2016; 2017), Jones et al. (2018; 2019; 2020) and Skjelvan et al. (2021), while spinoff from these projects have been presented in Skjelvan et al. (2014; 2016) and Skjelvan and Omar (2015). The precursor for these programs was Tilførselprogrammet, which existed between 2009 and 2012 (Johannessen et al., 2011, Chierici et al., 2012; 2013).

3. Methods and Data

Due to the Covid-19 pandemic and corresponding cancellation of cruises and fieldwork, the planned sampling scheme has still undergone some slight modifications; however, the list of performed activities in 2021 is still comprehensive. The data collected in the Ocean Acidification Monitoring program in 2021 are presented in ***Table 1***. Most of the data are available in international databases such as CDIAC (http://cdiac.ornl.gov/oceans/CARINA/) and SOCAT (www.socat.info). The data are also published in the database 'Vannmiljø' (www.vannmiljo.miljodirektoratet.no) of the Norwegian Environment Agency, as well as archived in the Norwegian Marine Data Centre (NMDC). Only new stations and sections as well as data from continuous measurements are presented in more detail in this report, in addition to the overview of the full monitoring activities presented in ***Table 1***.

Tabell 1 [Tittel]
A summary of transects and cruises within the Ocean Acidification Monitoring program where sampling was performed in 2021. Temperature and salinity are measured at all stations.

Section/station (sample type)	Sampling month	Depth	Variables	Institution	Financing
Torungen-Hirtshals (discrete)	February	Water column	A_T, C_T, nutrients	IMR	Environment Agency
Svinøy-NW (discrete)	March	Water column	A_T, C_T, nutrients	IMR	Environment Agency
Gimsøy-NW (discrete)	March (standard), April (extended)	Water column	A_T, C_T, nutrients	IMR	Environment Agency
Fugløya-Bjørnøya (discrete)	March	Water column	A_T, C_T, nutrients	IMR	Environment Agency
N. Barentshav (discrete)	September	Water column	A_T, C_T, nutrients	IMR	Environment Agency/ FRAM
Utsira (discrete)	January	Water column	A_T, C_T, nutrients	IMR	Environment Agency

Tromsø-Longyearbyen (discrete)	June, September, October, December	Surface	A_T, nutrients	NIVA	Environment Agency
Tromsø-Longyearbyen (continuous)	May-December	Surface	pCO2, pH	NIVA	Environment Agency /RCN
Oslo-Kiel (discrete)	June, September, November	Surface	A_T, C_T, nutrients	NIVA	Environment Agency
Oslo-Kiel (continuous)	July-December	Surface	pCO2, pH	NIVA	Environment Agency /RCN
Bergen-Kirkenes (discrete)	June, November	Surface	A_T, C_T, nutrients	NIVA	Environment Agency
Station M (discrete)	January, July (x2), November (x2)	Water column	A_T, C_T, nutrients	NORCE/ UiB	Environment Agency
Coastal station Skrova (discrete)	January, February, May, June (x2), July, August (x2), September, October, November	Water column	A_T, C_T, nutrients	IMR	Environment Agency
Coastal station Arendal (discrete)	Monthly: January-November	Water column	A_T, C_T, nutrients	IMR	Environment Agency
Ytre Hardangerfjord station - VT69 (discrete)	January, April, May, July, September, November	Water column	A_T, C_T, nutrients	NORCE*	Environment Agency
Korsfjorden station - H7 (discrete)	January, April, May, July, September, November	Water column	A_T, C_T, nutrients	NORCE*	Environment Agency
M/S Trans Carrier (discrete)**	November	Surface	A_T	NORCE	Environment Agency**
Tisler (discrete)	Monthly: February-October	Water column	A_T, C_T, nutrients	IMR	Environment Agency
Straumsfjorden station - VR54 (discrete)	Monthly: January - December	Water column	A_T, C_T, nutrients, Chl a	NIVA/ApN	Environment Agency, NIVA
Stjernsund coral reef (discrete)	April, June	Water column	A_T, C_T, nutrients	IMR	Environment Agency
Hardanger coral reefs (discrete)	April, July	Water column	A_T, C_T, nutrients	IMR	Environment Agency

Isfjorden/Grønfjorden station - SVR1 (discrete)	Monrhtly: May - September	Water column	A_T, C_T, nutrients, Chl a	NIVA/ApN	Environment Agency

A_T = Total Alkalinity, C_T = Dissolved Inorganic Carbon, pCO_2 = partial pressure of CO_2, Chl *a* = chlorophyll *a*
* NORCE uses UiB (University of Bergen) and IMR as subcontractors.
** NORCE OA activity (“Status of knowledge of ocean acidification in Sognefjorden”) financed by the Environment Agency.

In ***Figure 1***, an overview of positions for sections, transects, and fixed stations that were part of the Ocean Acidification Monitoring program in 2021 is shown.

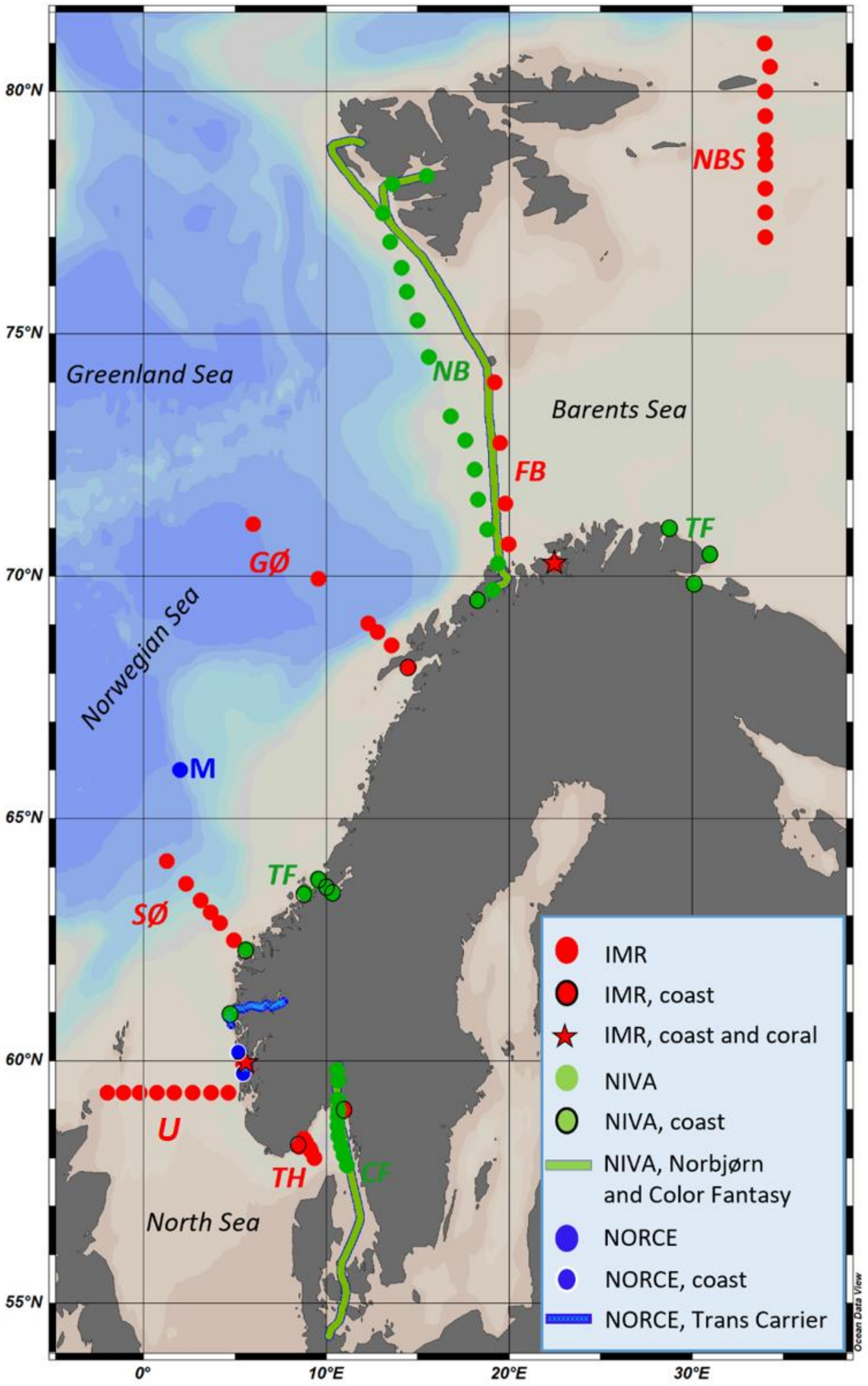


***Figure 1a**. Map showing the stations being part of the program Ocean Acidification Monitoring of Norwegian waters in 2021 and one additional OA activity. Red dots show transects where the water column is sampled; TH=Torungen-Hirtshals, U=Utsira, SØ=Svinøy-NW, GØ=Gimsøy-NW, FB=Fugløya-Bjørnøya, and NBS=Northern Barents Sea. Red dots with black outline show coastal stations, and red star with black outline indicate coral reef stations (see Figure 1b). Green lines with blue border show surface underway sensor measurements at M/S Color Fantasy (CF) and M/S Norbjørn (NB), and the green dots show positions of surface samples collected from these ships. The green dots with black outline show coastal surface samples collected from M/S Trollfjord (TF) in addition to one water column station in the north (see Figure 1b). The blue dot is Station M where the water column is sampled, and the blue dots with white rings are coastal water column stations (see Figure 1b). The light blue crosses on dark blue background are surface samples collected from M/S Trans Carrier (see Table 1)*.

***Figur 1a**. Kart over stasjoner som har inngått i programmet Havforsuringsovervåkning av norske farvann 2021 samt en ekstra havforsuringsaktivitet. Røde prikker viser snitt der prøver er samlet inn fra hele vanndypet; TH=Torungen-Hirtshals, U=Utsira, SØ=Svinøy-NV, GØ=Gimsøy-NV, FB=Fugløya-Bjørnøya og NBS=stasjoner i nordøstlige Barentshav. Røde prikker med svart kant viser kyststasjoner, og røde stjerner med svart kant er korallrev (se Figur 1b). Grønne linjer viser underveismålinger; CF=M/S Color Fantasy og NB=M/S Norbjørn. Grønne prikker viser overflatestasjoner samlet inn fra disse skipene. Grønne prikker med svart kant viser kystprøver samlet inn fra M/S Trollfjord (TF) og en kyststasjon i nord (se Figur 1b). Blå prikk (M) viser Stasjon M der prøver er samlet inn fra hele vanndypet, og blå prikker med hvit ring er kyststasjoner (se Figur 1b). Lyseblå kryss på mørk blå bakgrunn viser overflateprøver samlet inn fra M/S Trans (se Tabell 1)*.

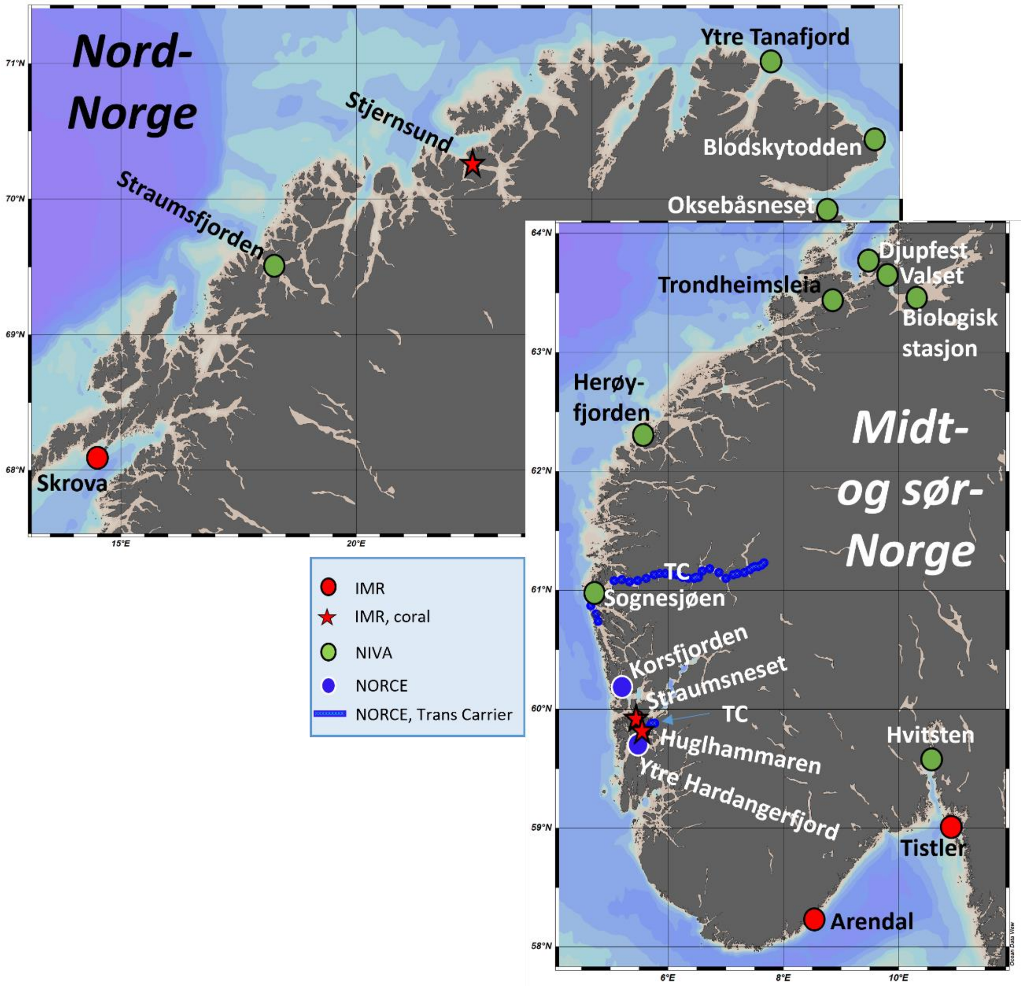


***Figure 1b**. Maps showing stations along the coast. Red, green, and blue colour indicate IMR, NIVA/ApN, or NORCE responsibility, respectively. Dots indicate surface or water column stations and stars are coral reef stations. Light blue crosses on dark blue background refers to sampling from M/S Trans Carrier.*

***Figur 1b**. Kart over kyststasjoner. Rød-, grønn- og blåfarge viser ansvarlig institusjon; henholdsvis IMR, NIVA/ApN eller NORCE. Prikker viser stasjoner fra overflata eller hele vanndypet og stjerner viser korallrevstasjoner. Lyseblå kryss på mørke blå bakgrunn viser innsamling fra M/S Trans Carrier.*

The Environment Agency has funded the sampling activities presented in this report. Methods are described more thoroughly in Skjelvan et al. (2021) and Jones et al. (2020). In the Results section, we have included plots from new sampling sites and sections of temperature, salinity, pH (at total scale and in situ temperature), Ω aragonite, dissolved inorganic carbon and total alkalinity.

4. Results

4.1 North Sea and Skagerrak

4.1.1 Utsira

In the North Sea, carbonate chemistry measurements were carried out by IMR on water samples from the whole water column at eight hydrographic stations along the Utsira section between Norway and the UK in January 2021 (***Figure 2)***. This region is strongly affected by the warm and salty Atlantic water (red) entering the northern part of the North Sea and fresh coastal waters (green, ***Figure 3)*** that characterise the oceanic conditions along the western coast of Norway.

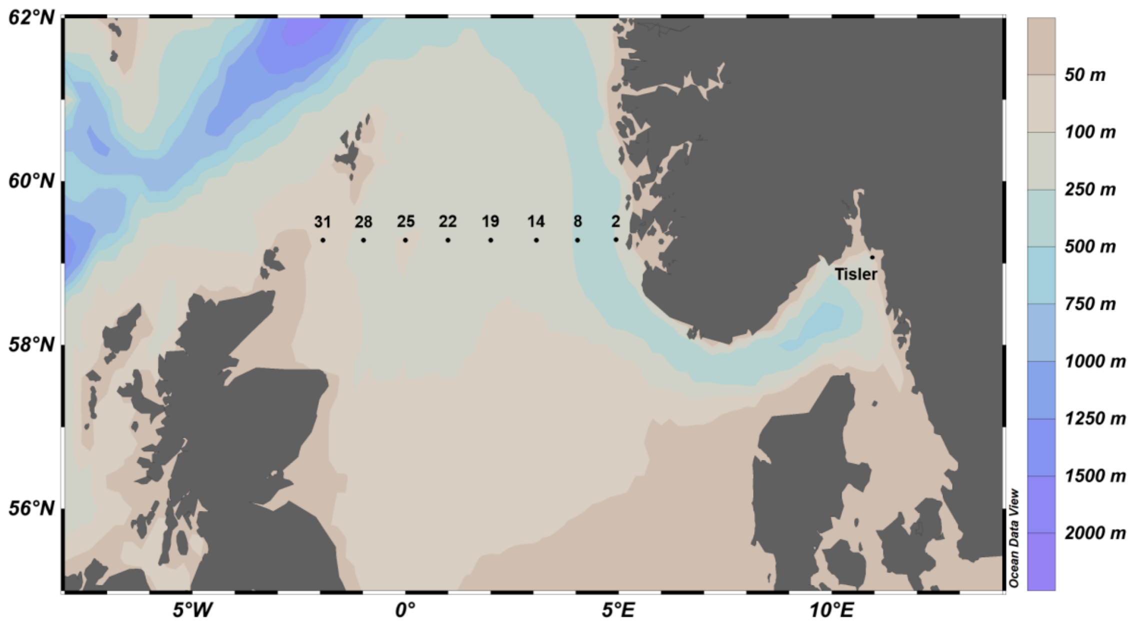


Figure 2. *Stations from the Utsira and the from the Tisler reef.*

Figur 2. *Stasjoner fra Utsira snittet og fra Tisler rev.*

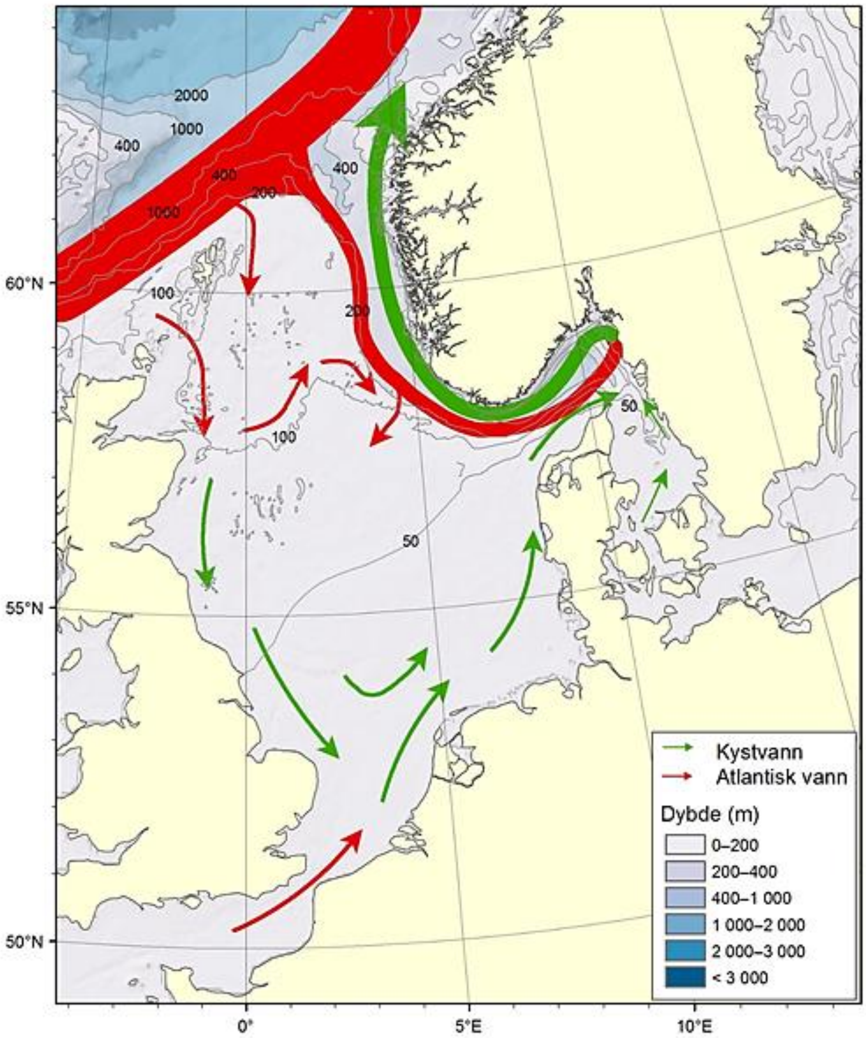
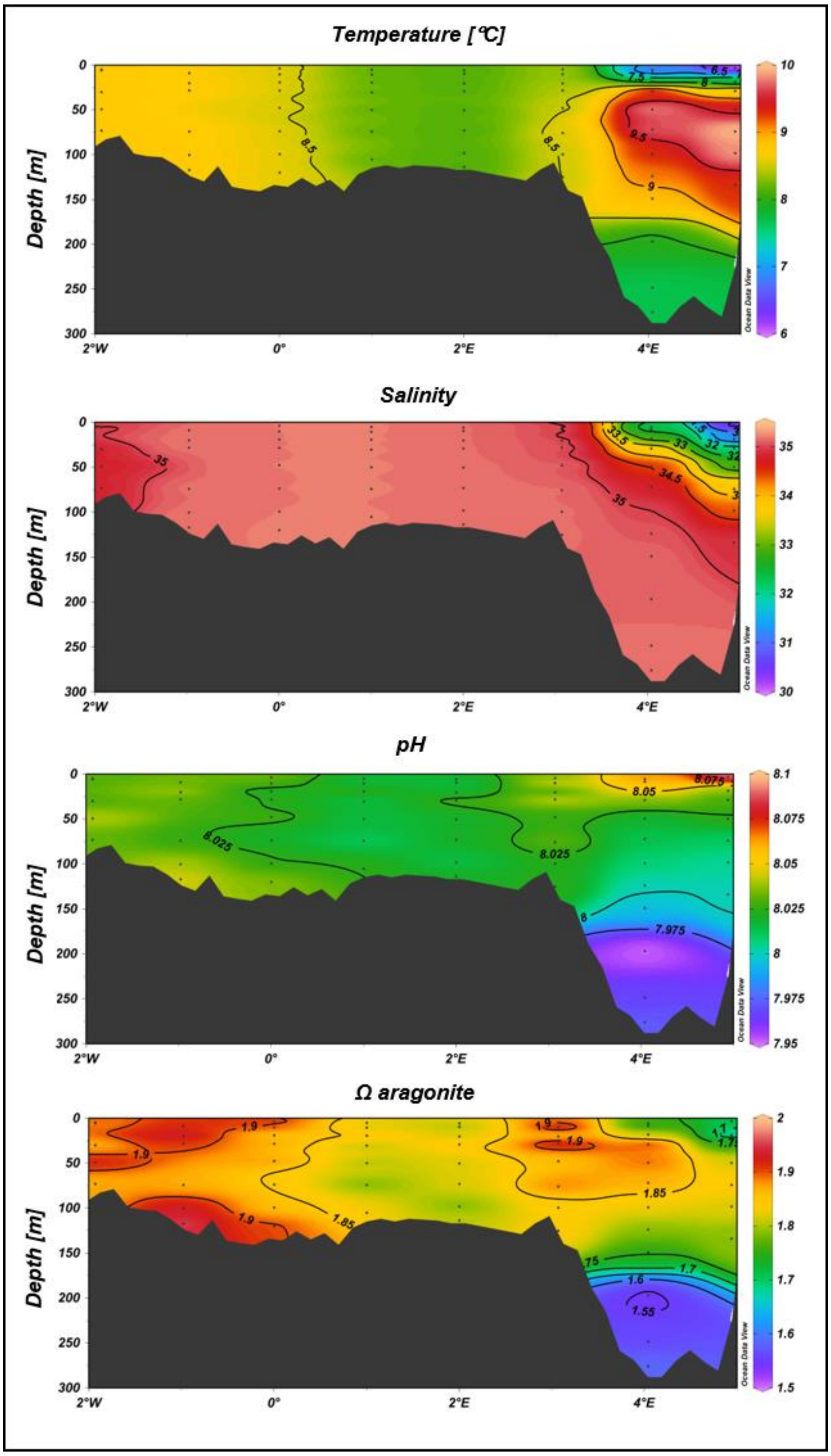


Figure 3*. Schematic map of the main currents in the North Sea and Skagerrak regions. The red arrows indicate the influx of Atlantic water, mostly at 100-200 m, while the green arrows indicate the main circulation patterns of coastal waters, typically in the top 20 m (www.imr.no). The Norwegian coastal current receives inputs from the southern North Sea and the Baltic Sea.*

Figur 3. *Skjematisk kart over de viktigste transportveiene i Nordsjøen og Skagerrak. De røde pilene indikerer innstrømning av atlantisk vann, for det meste i 100-200 m dyp, mens de grønne pilene angir hovedretningene til sirkulasjon av kystvann, som typisk strømmer i de øverste 20 m (www.imr.no). Kyststrømmen får tilførsler fra Nordsjøen og Østersjøen.*

The section extends from the Norwegian coast with cooler and fresher surface water and Atlantic influenced waters in subsurface layers across the North Sea. Close to the Norwegian coast, strong vertical gradients separate the cooler (~6 °C) and fresher (salinity ~30.4) surface layer with the underlying Atlantic water, which is distinguished by warmer (~10 °C) and salty (34-35) water below about 25 m depth (***Figure 4***). This was accompanied by increasing C_T and

A_T from lowest values of 2069 and 2219 µmol kg^{-1}, respectively, in the fresh water influenced surface layer to high values (C_T ~2180 µmol kg^{-1}; A_T ~2330 µmol kg^{-1}) below 150 m depth.



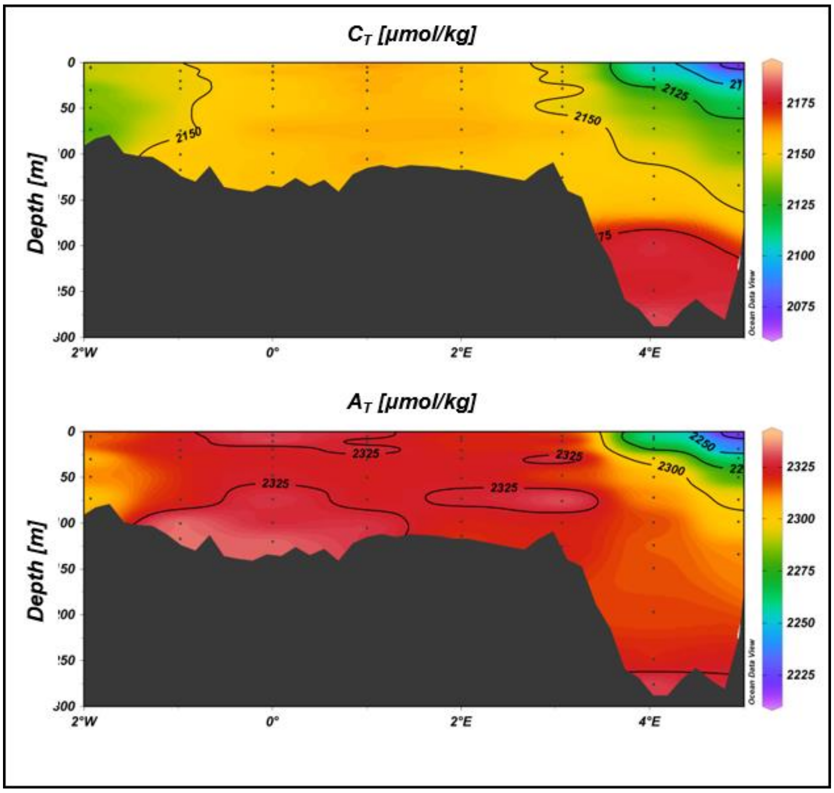


Figure 4. *Temperature (°C), salinity, pH, Ω aragonite, C_T and A_T along the Utsira section in January 2021. Black dots indicate sampling depths.*

Figur 4. *Temperatur (°C), saltholdighet, pH, Ω aragonitt, C_T og A_T langs snittet Utsira i januar 2021. Svarte prikker viser prøvedyp.*

Highest pH of 8.09 occurred in the cool and fresh surface water influenced by Norwegian coastal waters. Lowest pH of 7.95 and Ω aragonite 1.54 were found in the deeper parts of the section to the east at 200 m depth. Extending west along the section, the water column was more homogenous across the North Sea. The distribution of temperature and salinity show a slighter salty, cooler (salinity >35, ~8 °C) water column in the central part of the section and less salty and warmer (salinity 34.5-35, ~8.5-9 °C) waters closer to the UK. These slight spatial variations result from increased influences of Atlantic water in the central part of the section resulting in higher A_T up to 2336 µmol kg^{-1} and C_T ~2155 µmol kg^{-1} in the whole water column. The pH was in the range 8.02-8.04 and Ω aragonite of 1.85-1.96, with slightly elevated values in the western end of the section towards the UK.

4.1.2 Tisler

The Tisler reef in the Skagerrak (***Figure 1b, 2***) is constructed from dense colonies of the eye coral *Lophelia pertusa* that grows in a 1200 x 200 m large area east of the island of Tisler (***Figure 5***).

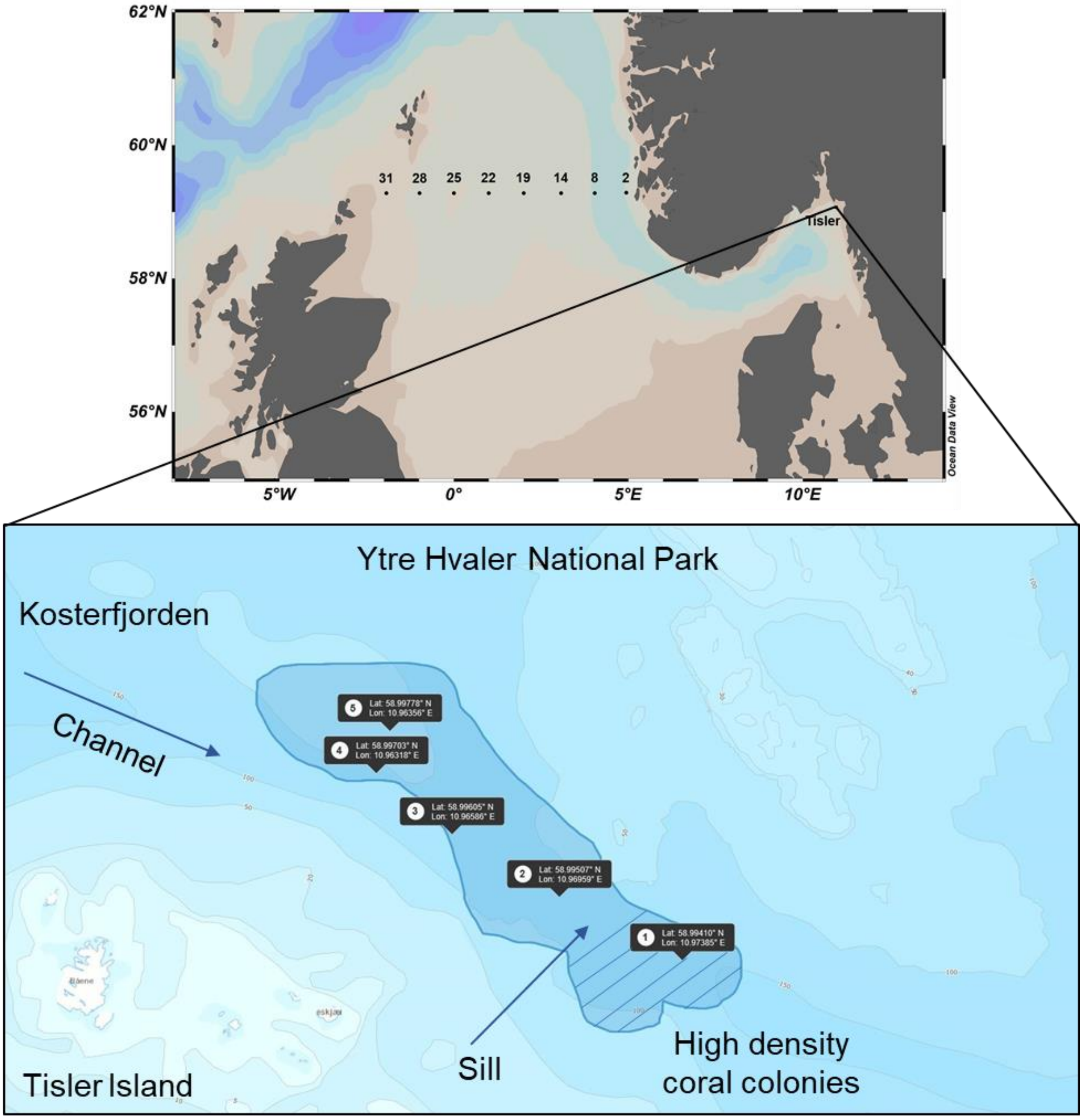
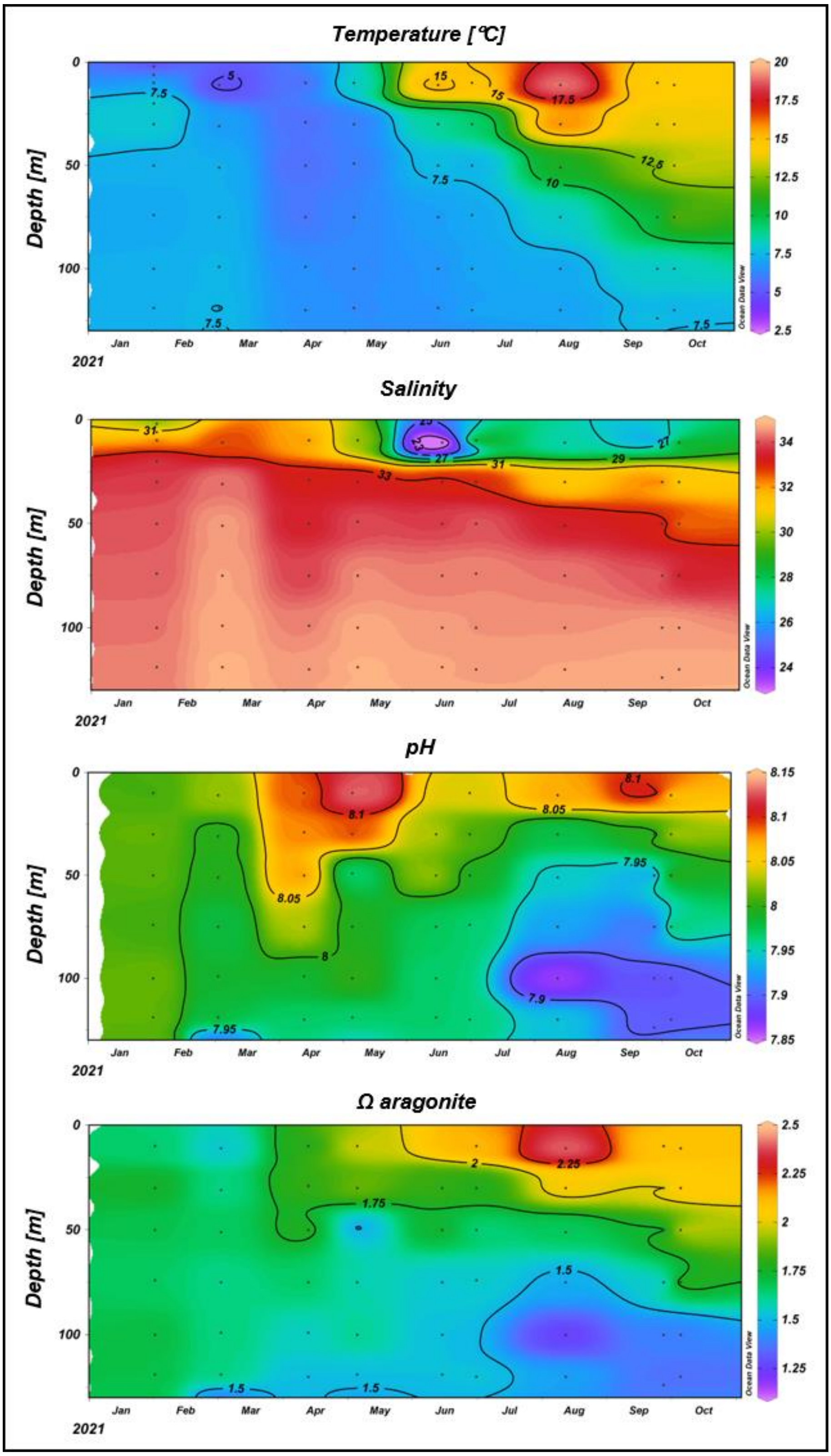


Figure 5. *The map shows the area around coral reefs at Tisler. Created from the Norwegian Environment Agency's map database. Approx. the distribution of the reef (dark blue area) is taken from Clippele et al (2018).*

Figur 5*. Kartet viser området rundt korallforekomster ved Tisler. Skapt ifra miljødirektoratets kartdatabase. Ca. utbredelsen av revet (mørkeblått område) er hentet fra Clippele et al (2018).*

Deep water from the Norwegian Channel is forced up over the threshold into Angrerenna and Kosterfjorden and creates a good environment and habitat for deep-water fauna (Clippele et al 2018). The living conditions for coral in the area appear to have been stable over time and it is estimated that the Tisler reef is at least 6000 years old (Dahl et al. 2012). The Tisler reef is the largest deep-water coral reef in the Skagerrak and has been protected since 2009 with its location in Ytre Hvaler National Park. Living colonies of *Lophelia pertusa* grow over large parts of the threshold area at 70-160 m depth, but it is the south-eastern part of the threshold where the largest densities occur and with 100% cover of living coral (Clippele et al. 2018). The area is characterised by complex hydrodynamics with alternating in- and outflow of water and occasionally with vertical flow that carries surface water with a high content of fresh organic material down to the reef (Wagner et al. 2011; Guihen et al. 2012).

Sampling at the Tisler reef was carried out from February (4 sites; Tisler 1-4; ***Figure 5***) and then monthly to October 2021 (2 sites; Tisler 1 and Tisler 5; ***Figure 5***) by IMR. This region of the Skagerrak is influenced by the interaction of fresher coastal waters in the upper 20 m and salty and warm Atlantic from the North Sea water below 100 m depth (***Figure 3***). Monthly changes in salinity showed strong seasonality in the upper 25 m of the water column at Tisler 1 (***Figure 6***) and Tisler 5 (***Figure 7***). Reductions in salinity to around 20-24 in June at both sites is due to the spring freshet with enhanced freshwater input from rivers due to rainfall and snowmelt, combined with influences of the colder and fresher coastal current. Freshwater dilution reduced A_T to low values around 2016 µmol kg^{-1} corresponding to the reductions in salinity. Deep vertical mixing during autumn and early winter increased salinity up to 34.97 in the water column as the underlying salty Atlantic water mixed into the surface layer. Seasonal warming increased temperatures to about 19°C in the surface layer and together with salinity changes resulted in stratification of the upper water column during spring and summer. Biological production reduced C_T to lowest values of 1880 µmol kg^{-1} in the upper 25 m, combined with dilution effects. High pH was found in the upper 25 m with maximum values up to 8.13 in May.


Temperature [°C]
Depth [m]
Jan Feb Mar Apr May Jun Jul Aug Sep Oct
2021
Salinity
pH
Ω aragonite
Ocean Data View

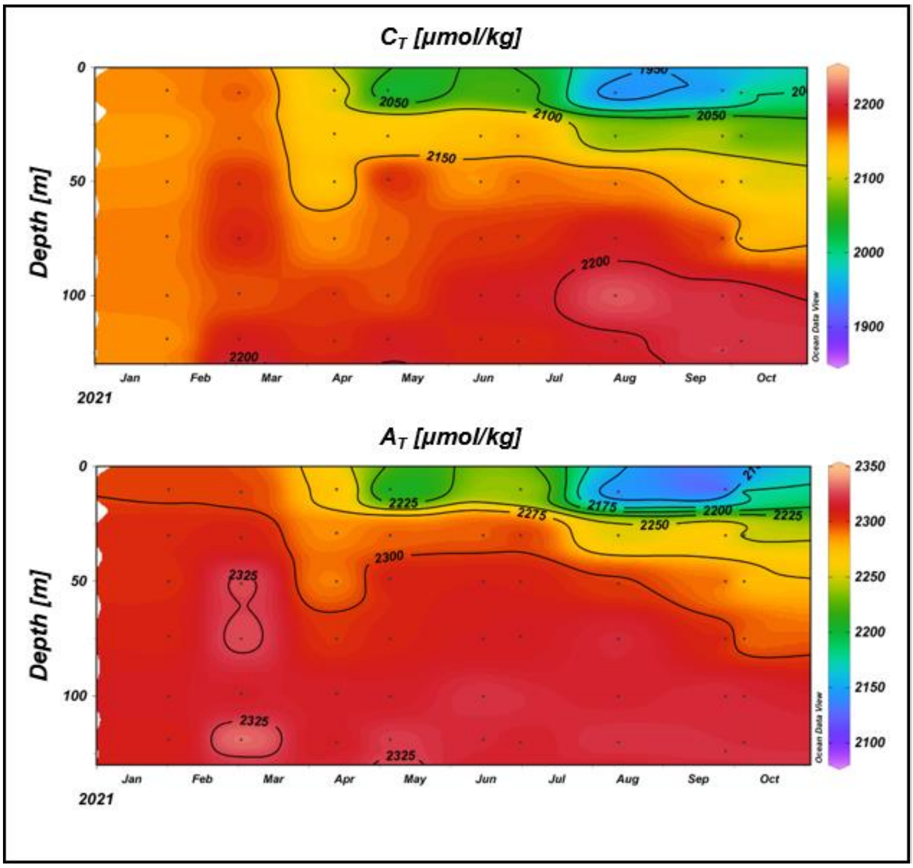
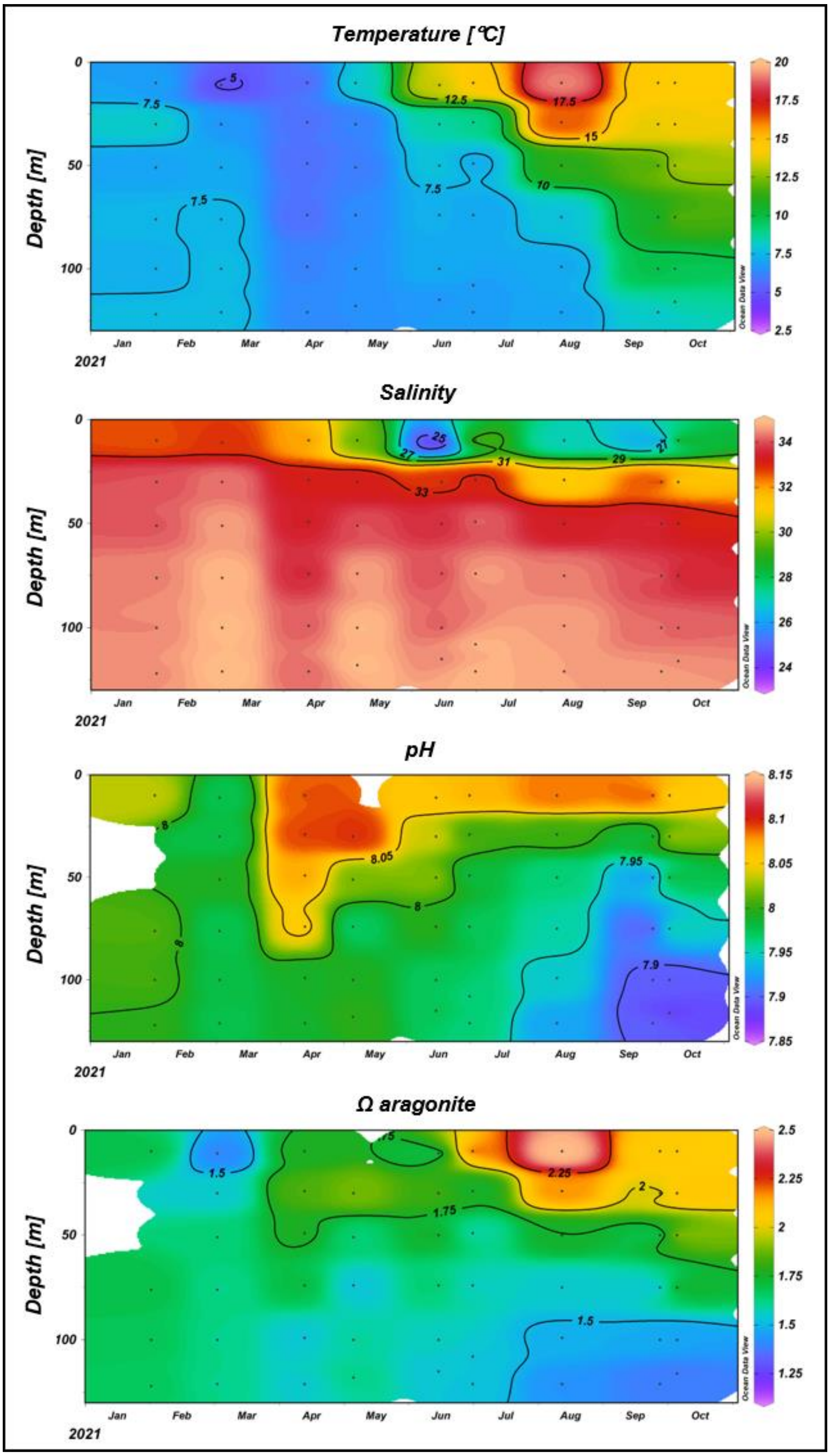


***Figure 6**. Monthly temperature (°C), salinity, pH, Ω aragonite, C_T and A_T in the upper 130 m at Tisler reef site 1 in 2021. Black dots indicate sampling depths.*

***Figur 6**. Månedlig temperatur (°C), saltholdighet, pH, Ω aragonitt, C_T og A_T i de øverste 130 m ved Tisler rev områder 1 i 2021. Svarte prikker viser prøvedyp.*

Lowest pH in the surface layer occurred in winter likely as a result of mixing of sub-surface water high in CO_2 and with corresponding low pH (***Figure 6-7***). Below the surface layer, the influence of Atlantic water could be distinguished by lower pH water being projected upwards in the water column. Ω aragonite was highest at 2.4-2.5 in the surface layer in August where biological production had reduced C_T and water temperatures were higher. Lower pH and Ω aragonite in the surface layer generally corresponded to periods of lower salinity, and lower A_T, from freshwater inputs and natural variability in the coastal current at this location. Lowest values of pH and Ω aragonite in the subsurface layers occurred with the intrusions of higher-C_T water were found from late summer approaching 100 m depth.


Temperature [℃]
Salinity
pH
Ω aragonite
Depth [m]
0
50
100
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
2021
Ocean Data View

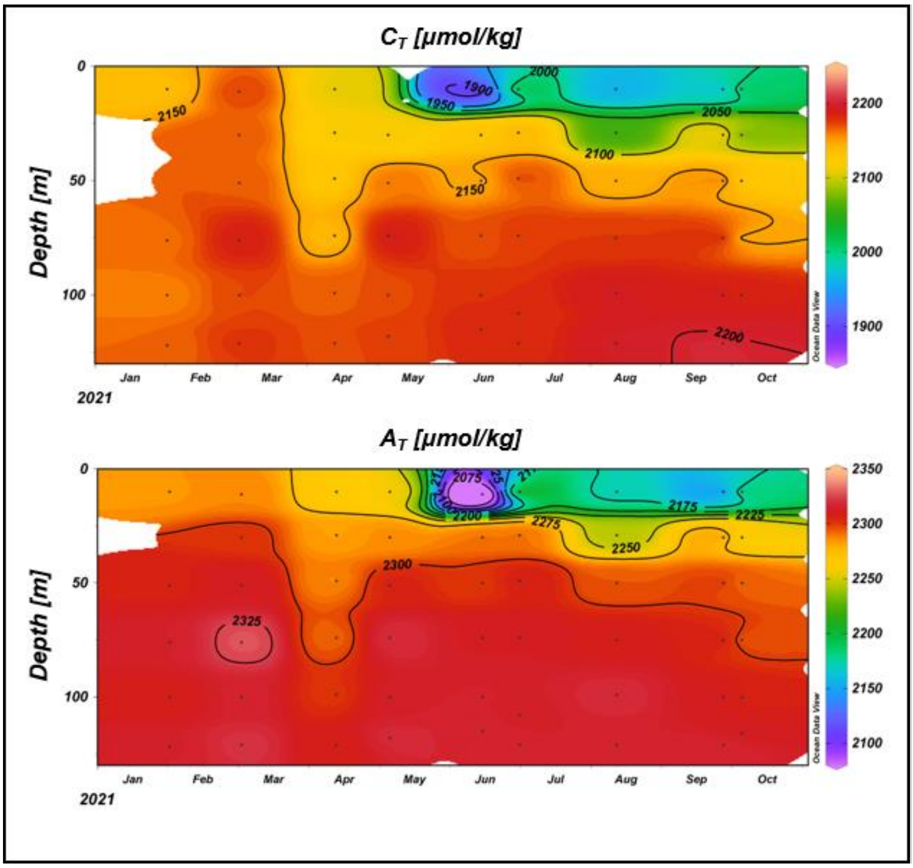


Figure 7*. Monthly temperature (°C), salinity, pH, Ω aragonite, C_T and A_T in the upper 130 m at Tisler reef site 5 in 2021. Black dots indicate sampling depths.*

Figur 7*. Månedlig temperatur (°C), saltholdighet, pH, Ω aragonitt, C_T og A_T i de øverste 130 m ved Tisler rev områder 5 i 2021. Svarte prikker viser prøvedyp.*

4.2 Continuous FerryBox measurements

Due to the COVID pandemic, there were challenges with some of the ships that are equipped by NIVA with FerryBoxes for continuous measurements. This was due to several operational aspects. 1) Ships were taken out of service by ship companies, in part due to lower passenger demand on M/S Color Fantasy and M/S Trollfjord, 2) Access to ship engine rooms where FerryBox instruments are installed was restricted either entirely or limited to port calls, 3) Travel to port locations were limited by national restrictions on travel, especially in the beginning and end of 2021, and 4) Personnel capacity was lower than usual due to sickness either from COVID or COVID-like symptoms in which they were unable to come to work and board FerryBox ships. In combination, these factors severely affected FerryBox maintenance and operations in 2021.

For discrete samples of ocean acidification and coastal water quality (ØKOKYST) on the routes Oslo-Kiel and Bergen-Kirkenes, sampling was coordinated with other sampling campaigns and projects (i.e. ØKOKYST local samplers and UiO ship F/F Braarud). This allowed most stations to be sampled according to the planned schedule, during the periods when the ships were not in operation.

As replacements for continuous data on ships out of operation due to COVID, it was agreed with Miljødirektoratet that additional discrete sampling would be done as compensation. For Oslo-Kiel one extra sampling for C_T/A_T and nutrients was done, giving a total of 3 sampling rounds in 2021 (9 stations). On Tromsø-Longyearbyen, two extra samplings were made (A_T, nutrients only), giving a total of four sampling rounds in 2021 (15 stations). For the first time in the Ocean acidification monitoring program, we also performed two manned cruises with Kong Harald on the route Bergen-Kirkenes, taking samples of C_T/A_T and nutrients on stations used for ØKOKYST (9 stations).

4.2.1 Oslo-Kiel

The ship used on the route Oslo-Kiel (M/S Color Fantasy) was taken out of operation for large parts of 2021. The ship started sailing again in June, and the FerryBox system was operational (***Figure 8-9***). Until September there was very restricted access to come onboard and do necessary maintenance and repairs, which impacted data quality for selected sensors (see red shaded area in ***Figure 8***).

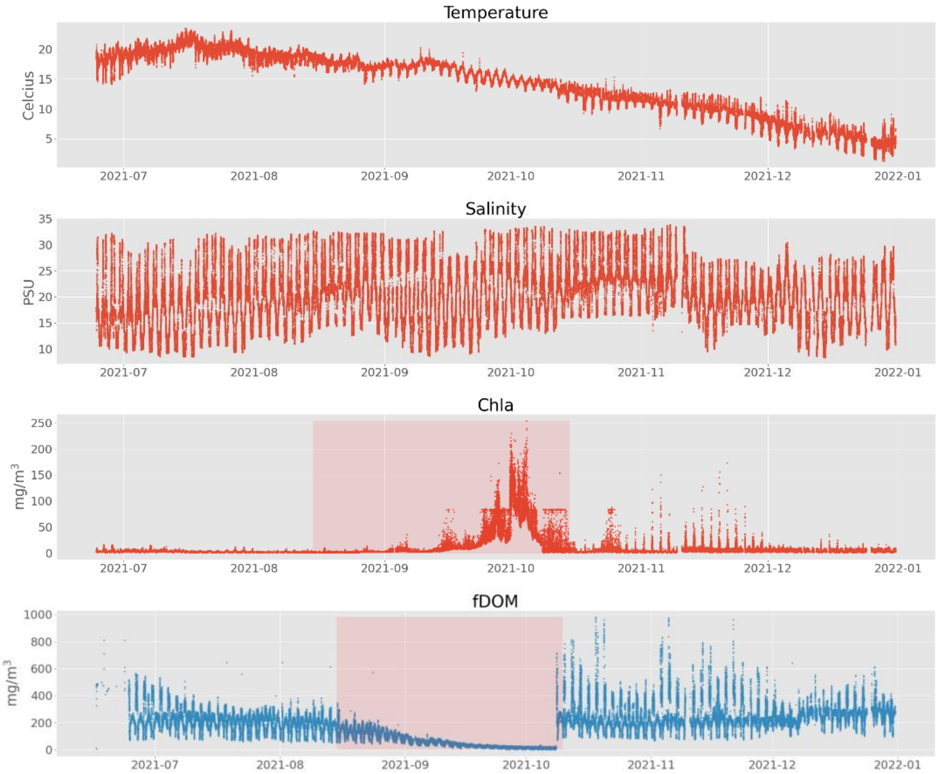


Figure 8. *Data coverage of FerryBox sensors on M/S Color Fantasy on the route Oslo-Kiel in 2021, for temperature (°C), salinity, chlorophyll a fluorescence (mg/m^3) and cDOM fluorescence (mg/m^3). Red shaded areas indicate periods with biofouling on sensors. Final (delayed-mode) quality control will be done before data reporting.*

Figur 8. *Datadekning for FerryBox sensorer på M/S Color Fantasy for ruten Oslo-Kiel i 2021, for temperatur (°C), saltholdighet, klorofyll a fluoresens (mg/m^3) og cDOM fluoresens (mg/m^3). Rødt skravert område viser periode med biofouling på sensorer. Data vil gjennomgå endelig kvalitetskontroll før datarapportering.*

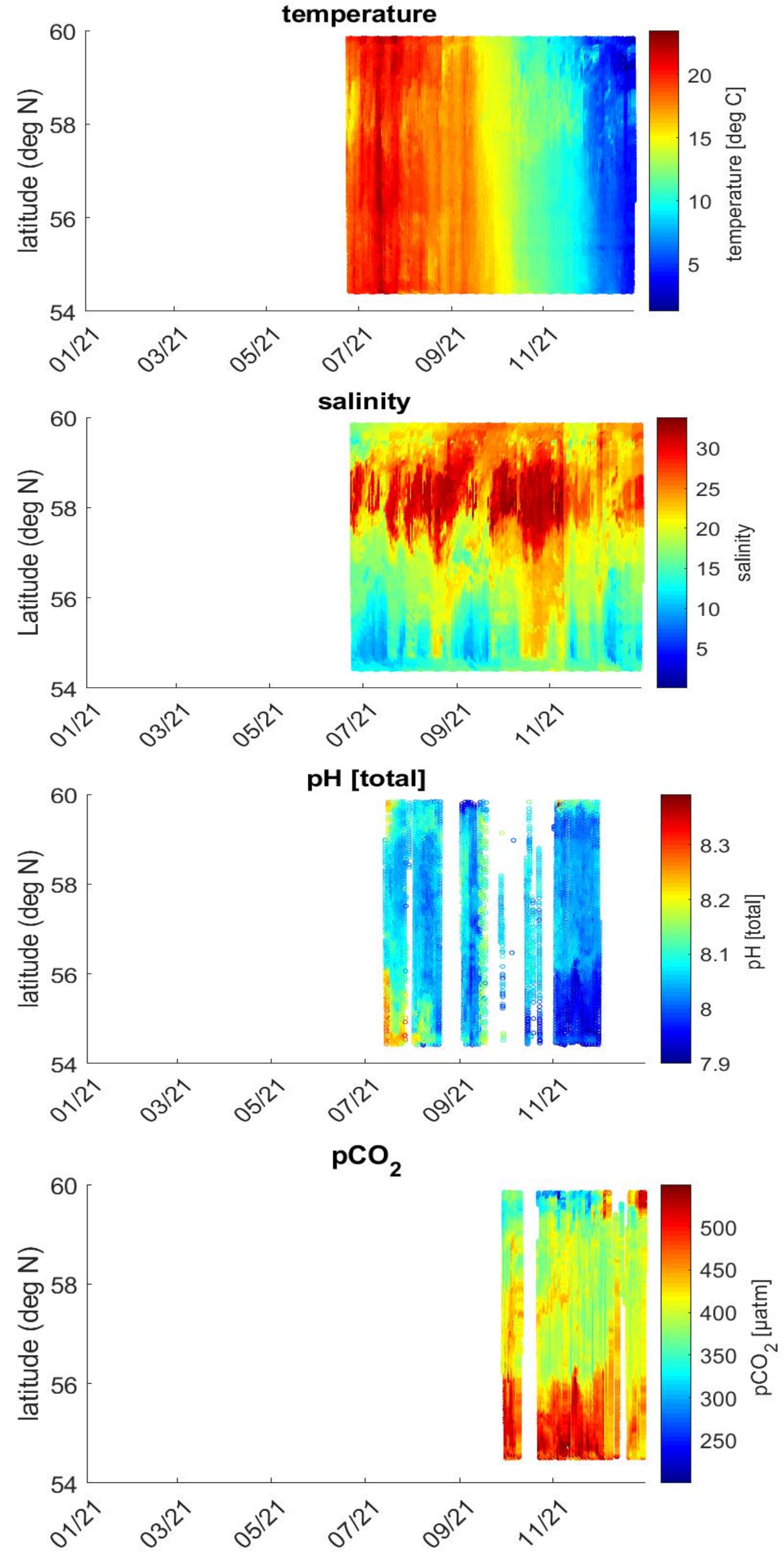

temperature
latitude (deg N)
temperature [deg C]
salinity
Latitude (deg N)
salinity
pH [total]
latitude (deg N)
pH [total]
pCO2
latitude (deg N)
pCO2 [µatm]
01/21
03/21
05/21
07/21
09/21
11/21

Figure 9. *Continuous measurements of temperature (°C), salinity, pH and pCO_2 (µatm) sensors on M/S Color Fantasy on the route Oslo-Kiel in 2021.*

Figur 9. *Kontinuerlige målinger av temperatur (°C), saltholdighet, pH og pCO_2 (µatm) sensorer på M/S Color Fantasy for ruten Oslo-Kiel i 2021.*

4.2.2 Bergen-Kirkenes

For the Bergen-Kirkenes route the ship M/S Trollfjord equipped with FerryBox for the period 2017-2020 was taken out of operation, and a new micro-FerryBox system was manufactured and installed in July 2021 on the ship M/S Kong Harald that operates the same route (***Figure 10***). Due to restricted access and motor problems on the ship the pH sensor was installed in September and pCO_2 sensor in October. The new installation on M/S Kong Harald was a large undertaking and had to happen quickly while the ship was in operation (while in port in Bergen), and when inspecting discrete measurements taken for ØKOKYST FerryBox we detected that the inlet recommended by the engine room staff was contaminated from the waste water outlet of the ship. The contaminated ØKOKYST discrete samples were not reported to Vannmiljø, the pH and pCO_2 data were compromised due to contamination, and a similar thorough quality control of the remaining sensor data and C_T/A_T samples will also be done before the reporting of OA data in June 2022 (data not shown). The FerryBox system on M/S Kong Harald was dismounted in February 2022, and a re-installation of the FerryBox system onboard M/S Trollfjord was done in March 2022.

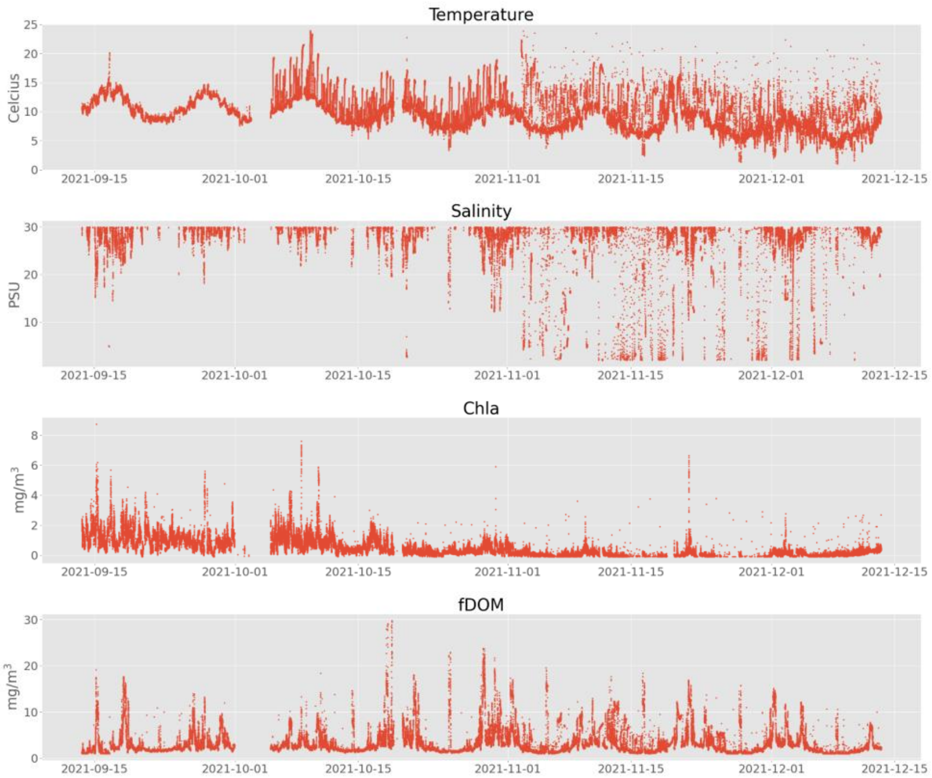


Figure 10. *Data coverage of FerryBox sensors on M/S Kong Harald on the route Bergen-Kirkenes in 2021, for temperature (°C), salinity, chlorophyll a fluorescence (mg/m^3) and cDOM fluorescence (mg/m^3). Final (delayed-mode) quality control will be done before data reporting.*

Figur 10. *Datadekning for FerryBox sensorer på M/S Kong Harald for ruten Bergen-Kirkenesl i 2021, for temperatur (°C), saltholdighet, klorofyll a fluoresens (mg/m^3) og cDOM fluoresens (mg/m^3). Data vil gjennomgå endelig kvalitetskontroll før datarapportering.*

4.2.3 Tromsø-Longyearbyen

The ship M/S Norbjørn that operates the route from Tromsø-Longyearbyen was in operation during the whole COVID pandemic, however NIVA personnel were not allowed onboard, and the system had to be shut down in December 2020. In March 2021, personnel were allowed onboard and necessary repairs could be made so that the FerryBox system was operational (***Figure 11***). The pCO2 and pH sensors were operational from May 2021 (***Figure 12***). In August there was a major leakage in the system and the FerryBox system had to be shut down. When the ship was in dock in September, the system could be repaired and was functional for the remainder of the year.

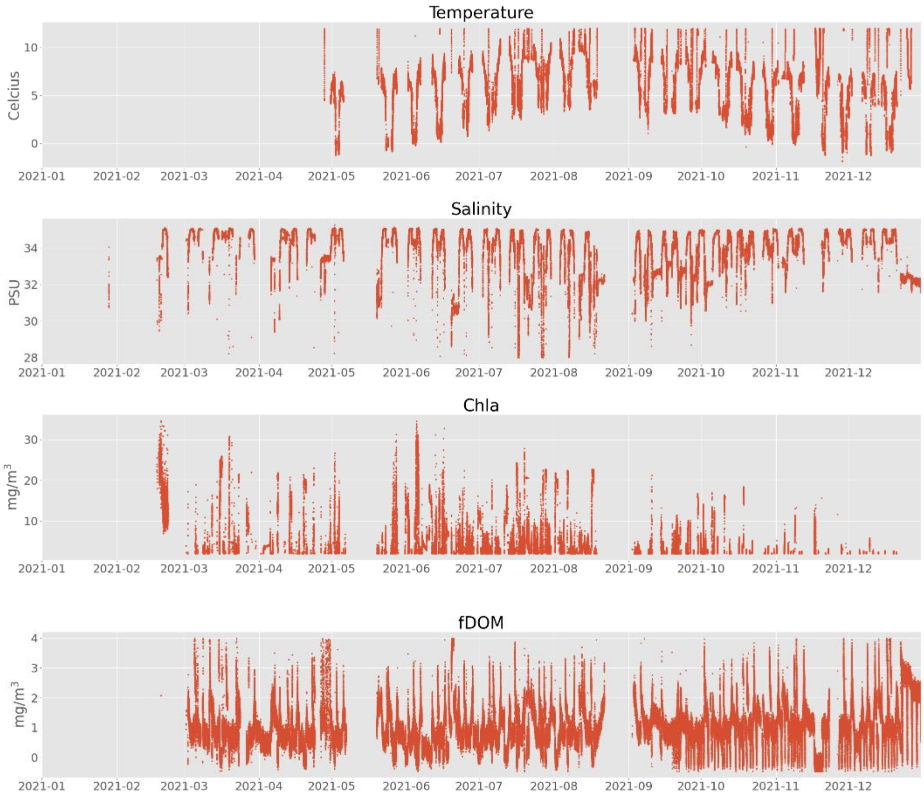
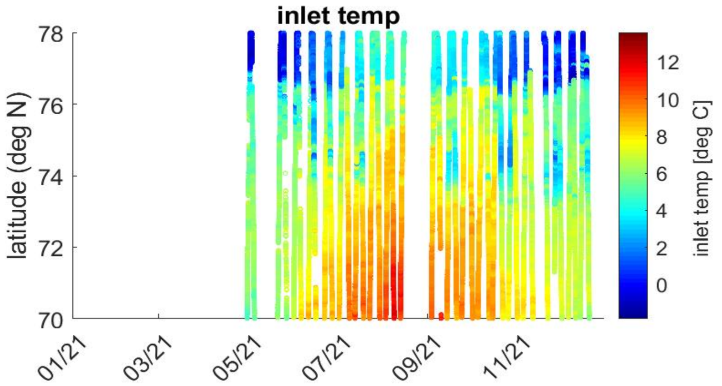
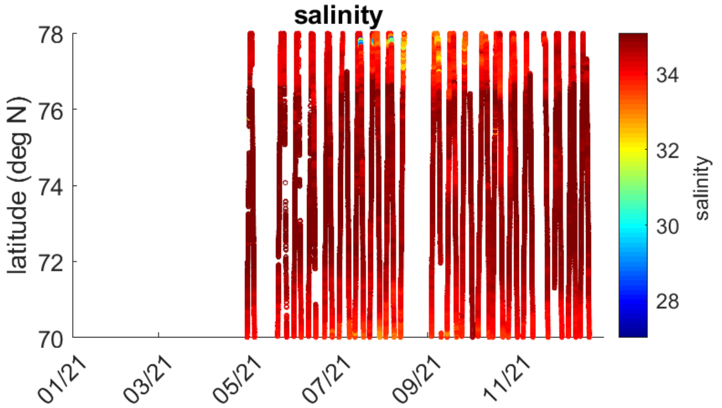
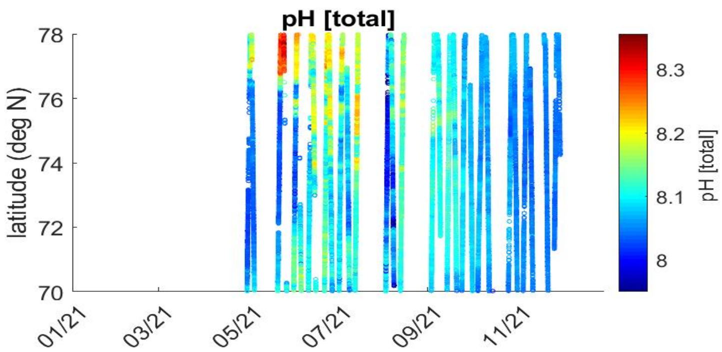


***Figure 11**. Data coverage of FerryBox sensors on M/S Norbjørn on the route Tromsø-Longyearbyen in 2021. for temperature (°C), salinity, chlorophyll a fluorescence (mg/m^3) and cDOM fluorescence (mg/m^3). Final (delayed-mode) quality control will be done before data reporting.*

***Figur 11**. Datadekning for FerryBox sensorer på M/S Norbjørn for ruten Tromsø-Longyearbyen i 2021, for temperatur (°C), saltholdighet, klorofyll a fluoresens (mg/m^3) og cDOM fluoresens (mg/m^3). Data vil gjennomgå endelig kvalitetskontroll før datarapportering.*


inlet temp
latitude (deg N)
78
76
74
72
70
01/21
03/21
05/21
07/21
09/21
11/21
12
10
8
6
4
2
0
inlet temp [deg C]


salinity
latitude (deg N)
78
76
74
72
70
01/21
03/21
05/21
07/21
09/21
11/21
34
32
30
28
salinity


pH [total]
latitude (deg N)
78
76
74
72
70
01/21
03/21
05/21
07/21
09/21
11/21
8.3
8.2
8.1
8
pH [total]

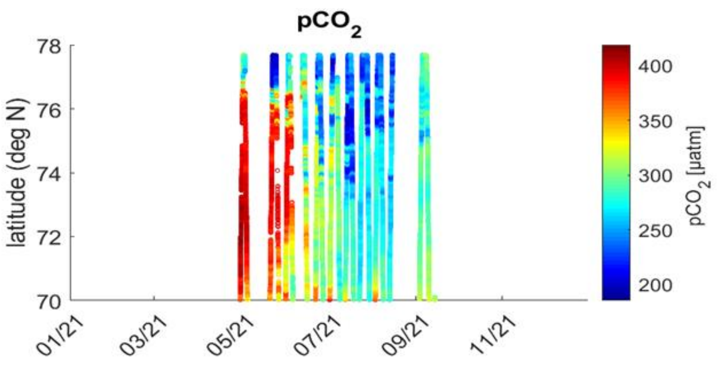

pCO_2
latitude (deg N)
78
76
74
72
70
01/21
03/21
05/21
07/21
09/21
11/21
400
350
300
250
200
pCO_2 [µatm]

Figure 12. *Continuous measurements of temperature (°C), salinity, pH and pCO_2 (µatm) sensors on M/S Norbjørn on the route Tromsø-Longyearbyen in 2021.*

Figur 12. *Kontinuerlige målinger av temperatur (°C), saltholdighet, pH og pCO_2 (µatm) sensorer på M/S Norbjørn for ruten Tromsø-Longyearbyen i 2021.*

5. References

Chierici, M., A. Fransson & L.G. Anderson. Influence of m-cresol purple indicator additions on the pH of seawater samples: correction factors evaluated from a chemical speciation model. *Mar. Chem*. 65(3-4), 281-290, 1999.

Chierici, M., K. Sørensen, T. Johannessen, K.Y. Børsheim, A. Olsen, E. Yakushev, A. Omar, S. Lauvset & T.A. Blakseth, Tillførselprogrammet 2011, Overvåking av havsførsuring av norske farvann, Rapport, Klif, TA2936 2012, 2012.

Chierici, M., K. Sørensen, T. Johannessen, K.Y. Børsheim, A. Olsen, E. Yakushev, A. Omar, I. Skjelvan, M. Norli, S. Lauvset & T.A. Blakseth, Tillførselprogrammet 2012, Overvåking av havforsuring i norske farvann, Rapport, Klif, TA3043 2013, 2013.

Chierici, M., I. Skjelvan, R. Bellerby, M. Norli, L. Lunde Fonnes, H. Hodal Lødemel, K.Y. Børsheim, S.K. Lauvset, T. Johannessen, K. Sørensen & E. Yakushev, Overvåking av havforsuring i norske farvann, Report (in Norwegian), Miljødirektoratet, M-218, 2014.

Chierici, M., I. Skjelvan, M. Norli, H.H. Lødemel, L.F. Lunde, K. Sørensen, E. Yakushev, R. Bellerby, A.L. King, S.K. Lauvset, T. Johannessen & K.Y. Børsheim, Overvåking av havforsuring i norske farvann i 2014, Report (in Norwegian), Miljødirektoratet, M-354, 2015.

Chierici, M., I. Skjelvan, M. Norli, K.Y. Børsheim, S.K. Lauvset, H.H. Lødemel, K. Sørensen, A.L. King, T. Kutti, A. Renner, A. Omar & T. Johannessen, Overvåking av havforsuring i norske farvann i 2015, Report (in Norwegian), Miljødirektoratet, M-573, 2016.

Chierici, M., I. Skjelvan, M. Norli, E. Jones, K.Y. Børsheim, S. K. Lauvset, H.H. Lødemel, K. Sørensen, A.L. King & T. Johannessen. Overvåking av havforsuring i norske farvann i 2016, Report (in Norwegian), Miljødirektoratet, M-776, 2017.

Dahl MP, Pereyra RT, Lundälv T, André C. 2012. Fine-scale spatial genetic structure and clonal distribution of the cold-water coral Lophelia pertusa. Coral Reefs.

De Clippele LH, Huvenne VAI, Orejas C, Lundälv T, Fox A, Hennige SJ, Rpberts JM. 2018. The effect of local hydrodynomics on the spatial extent and morphology of cold-water coral habitats at Tisler Reef, Norway. Coral Reefs 37: 253-266.

Dickson, A.G. & F.J. Millero. A comparison of the equilibrium constants for the dissociation of carbonic acid in seawater media. *Deep-Sea Res*. 34, 1733-1743, 1987.

Dickson, A.G. 1990. Standard potential of the reaction: AgCl(s) + ½H2(g) = Ag(s) + HCl(aq), and the standard acidity constant of the ion HSO4 – in synthetic sea water from 273.15 to 318.15 K. *J. Chem. Thermodyn.* 22: 113–127, 1990.

Dickson, A.G., C.L. Sabine, J.R. Christian (eds.). Guide to Best Practices for Ocean CO_2 Measurements. PICES Special Publication 3, IOCCP Report 8, 191 pp, 2007.

Guihen, D, White, M, Lundalv, T. 2012. Temperature shocks and ecological implications at a cold-water coral reef. Marine Biodiversity Records e68.

Ingle, S.E. 1975. Solubility of calcite in the ocean. Mar. Chem., 3.

Johannessen, T., K. Sørensen, K.Y. Børsheim, A. Olsen, E. Yakushev, A. Omar & T.A. Blakseth. Tilførselsprogrammet 2010. Overvåking av forsuring av norske farvann med spesiell fokus på Nordsjøen. Report (in Norwegian), KLIF, TA 2809-2011, 201

Jones, E., M. Chierici, I. Skjelvan, M. Norli, K.Y. Børsheim, H.H. Lødemel, T. Kutti, K. Sørensen, A.L. King, K. Jackson & T. de Lange. Monitoring of ocean acidification in Norwegian seas in 2017, Report, Miljødirektoratet, M-1072, 2018.

Jones, E., M. Chierici, I. Skjelvan, M. Norli, K.Y. Børsheim, H.H. Lødemel, K. Sørensen, A.L. King, S. Lauvset, K. Jackson, T. de Lange, T. Johannsessen & C. Mourgues. Monitoring ocean acidification in Norwegian seas in 2018, Report, Miljødirektoratet, M-1417, 2019.

Jones, E., M. Chierici, I. Skjelvan, M. Norli, H. Frigstad, K.Y. Børsheim, H.H. Lødemel, T. Kutti, A.L. King, K. Sørensen, S. K. Lauvset, K. Jackson-Misje, L.B. Apelthun, T. de Lange, T. Johannsessen, C. Mourgues og R. Bellerby. Monitoring ocean acidification in Norwegian seas in 2019, Report, Miljødirektoratet, M-1735, 2020.

Mehrbach, C., C.H. Culberson, E.J. Hawley & R.M. Pytkowicz. Measurements of the apparent dissociation constants of carbonic acid in seawater at atmospheric pressure. *Limnol. Oceanogr*. 18, 897-907, 1973.

Millero, F.J., Carbonate constants for estuarine waters, *Marine and Freshwater Research,* 61, 139-142.

Mintrop, L., F. Pérez, M. González-Dávila, J. Santana-Casiano & A. Körtzinger, Alkalinity determination by potentiometry: Intercalibration using three different methods, *Ciencias Marinas*, 26, 23–37, 2000.

Mucci, A. The solubility of calcite and aragonite in seawater at various salinities, temperatures and at one atmosphere pressure, *Am. J. Sci*., 283, 780–799.

Orr, J.C., V.J. Fabry, O. Aumont et al. Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature* 437, 681-686, 2005.

Pierrot, D., E. Lewis & D.W.R. Wallace. MS Excel Program Developed for CO2 System Calculations. ORNL/CDIAC-105a. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee.

Pierrot, D., C. Neill, K. Sullivan, R. Castle, R. Wanninkhof, H. Lüger, T. Johannessen, A. Olsen, R.A. Feely & C.E. Cosca. Recommendation for autonomous underway pCO_2 measuring systems and data-reduction routines, *Deep-Sea Res*. II, 56, 512-522, doi:10.1016/j.dsr2.2008.12.005, 2009.

Reggiani, E., A.L. King, M. Norli, P. Jaccard, K. Sorensen & R.G.J. Bellerby. FerryBox-assisted monitoring of mixed layer pH in the Norwegian Coastal Current. Journal of Marine Systems, doi: 10.1016/j.jmarsys.2016.03.017, 2016.

Seidel, M.P., M.D. DeGrandpre & A.G. Dickson. A sensor for in situ indicator-based measurements of seawater pH, *Mar. Chem*., 109, 18–28, 2008.

Skjelvan, I., E. Jeansson, M. Chierici, A. Omar, A. Olsen, S. Lauvset & T. Johannessen. Ocean acidification and uptake of anthropogenic carbon in the Nordic Seas, 1981-2013, Report (in Norwegian), Norwegian Environment Agency, M244, 2014.

Skjelvan, I. & A. Omar. Knowledge status on Ocean Acidification in fjords along the west coast of Nowaty, Report (in Norwegian), Norwegian Environment Agency, M-426, 2015.

Skjelvan, I., M. Chierici, K. Sørensen, K. Jackson, T. Kutti, H.H. Lødemel, A.L. King, E. Reggiani, M. Norli, R. Bellerby, E. Yakushev, A. Omar. Ocean Acidification in fjords at the west coast and CO2 variability in Lofoten, Norway, Report (in Norwegian), Norwegian Environment Agency, M-642, 2016.

Skjelvan, I., E. Jones, M. Chierici, H. Frigstad, K.Y. Børsheim, H.H. Lødemel, T. Kutti, A.L. King, K. Sørensen, A. Omar, R. Bellerby, G. Christensen, S. Marty, E. Protsenko, C. Mengeot, L. Valestrand, M. Norli, K. Jackson-Misje, L.B. Apelthun, T. de Lange, T. Johannessen, and C. Mourgues. Monitoring ocean acidification in Norwegian seas in 2020, Rapport, Miljødirektoratet, M-2056|2021.

Sutton, A.J., C.L. Sabine, S. Maenner-Jones, N. Lawrence-Slavas, C. Meinig, R.A. Feely, J.T. Mathis, S. Musielewicz, R. Bott, P.D. McLain, H.J. Fought & A. Kozyr. A high-frequency atmospheric and seawater pCO2 data set from 14 open-oceansites using a moored autonomous system, *Earth Syst. Sci. Data*, 6, 353-366, 2014.

Uppstrom L.R. The boron/chlorinity ratio of the deep-sea water from the Pacific Ocean. *Deep-Sea Res.* I 21 161-162,1974.

van Heuven, S., D. Pierrot, J.W.B. Rae, E. Lewis & D.W.R. Wallace. MATLAB Program Developed for CO2 System Calculations. ORNL/CDIAC-105b. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy, Oak Ridge, Tennessee. doi: 10.3334/CDIAC/otg.CO2SYS_MATLAB_v1.1, 2011.

Wagner H, Purser A, Thomasen L, Jesus CC, Lundälv T. 2011. Particulate organic matter fluxes and hydrodynamics at the Tisler cold-water coral reef. Journal of Marine Systems 85. 19-29.

6. Appendix

6.1 The carbonate system in seawater

The carbonate system in seawater is composed of 90% hydrogen carbonate (HCO_3^-), 9% carbonate (CO_3^{2-}), and ~1% dissolved CO_2 and carbonic acid (H_2CO_3). Atmospheric CO_2 absorbed by the sea reacts with water and forms carbonic acid, which immediately dissolves into HCO_3^- and hydrogen ion (H^+). Some of the free H^+ reacts with CO_3^{2-} to form HCO_3^-, and the net reaction is expressed in Eq.1, which describes the consumption of CO_3^{2-} and production of HCO_3^-:

$$CO_2 + CO_3^{2-} + H_2O \leftrightarrow 2HCO_3^- \quad (1)$$

CO_3^{2-} in the ocean is only slowly replenished through weathering of carbonate rocks or dissolution of sediments, and thus, the supply of new CO_3^{2-} cannot keep up with the consumption due to CO_2 uptake from the atmosphere. Thus, the amount of HCO_3^- in the ocean is increasing and that of CO_3^{2-} is decreasing. Since HCO_3^- is more acidic than CO_3^{2-}, the ocean becomes more acidic.

Furthermore, when large quantities of CO_2 are absorbed in the ocean and the concentration of CO_3^{2-} ions in seawater is reduced, this will also affect the stability of the calcium carbonate ($CaCO_3$) shells and skeletons of marine organisms, which is likely to becomes chemically unstable (Orr et al., 2005). Calcium carbonate ($CaCO_3$) is formed only biologically (Eq. 2) while the dissolution is a chemical process (Eq. 3).

$$Ca^{2+} + 2HCO_3^- \leftrightarrow CaCO_3(s) + H_2CO_3 \quad (2)$$

$$CaCO_3(s) \leftrightarrow Ca^{2+} + CO_3^{2-} \quad (3)$$

The carbonate system in seawater can be described by four measurable variables: Dissolved Inorganic Carbon (C_T), Total Alkalinity (A_T), partial pressure of CO_2 (pCO_2), and pH. When two of the variables are known, in addition to temperature, salinity, and the carbonate constants, the other two can be calculated. ***Table A1*** describes more in detail the four measurable carbonate variables in addition to other constituents of the carbonate system. For more info, see Jones et al. (2020).

The degree of calcium carbonate saturation (Ω calcite, Ω aragonite) is an indicator of the concentration of carbonates in the water, where $\Omega > 1$ means the water is oversaturated with respect to carbonate and $\Omega < 1$ means that the seawater is undersaturated with carbonate. For the latter situation, the chemical environment is unfavourable to organisms with carbonate shells, such as winged snails or coral reefs.

Table A1

Constituents of the seawater carbon system and their definitions.

Variable **Ion**	**Name**	**Explanation**
CO_2	Carbon dioxide	Gas in the atmosphere (natural and man-made origin) which is absorbed/emitted by the ocean
HCO_3^-	Hydrogen carbonate	Carbon ion which is abundant in seawater
CO_3^{2-}	Carbonate	Carbon ion, which is less abundant in seawater, plays a role in the degree of saturation (Ω)
C_T	Dissolved Inorganic Carbon	The sum of carbonic acid and dissolved CO_2 in water (CO_2*), HCO_3^- and CO_3^{2-}
A_T	Total Alkalinity	Capacity of water to neutralize acid (buffer capacity) and consists of the sum of the bases of the solution formed by weak acids
pH	pH	Measure of acidity that indicates the concentration of hydrogen ions (H^+) in water
pCO_2	Partial pressure of CO_2	Pressure of CO_2 if CO_2 gas is the only gas in a volume
Ω calcite Ω aragonite	Degree of saturation of calcite (Ca) and aragonite (Ar), which are two forms of calcium carbonate	Amount of CO_3^{2-} in water relative to the saturation concentration of CO_3^{2-}, relevant for dissolution of solid calcite or aragonite
Chl a	Chlorophyll a	The key pigment for photosynthesis and used as a measure of phytoplankton biomass

6.2 Measurements and methods

The program Ocean Acidification Monitoring uses internationally recognized methods and procedures for seawater sampling and instrumentation, as described in Dickson et al. (2007). In order to avoid the effects of continued biological activity, the discrete water samples for C_T and A_T were fixed with saturated mercury chloride solution and stored in the dark at approx. 4°C until analyses were performed, as recommended by Dickson et al. (2007). The measurement methods of the variables C_T, A_T, pH and pCO_2 are listed in ***Table A2***. For more information about the methods, see Jones et al. (2020).

Table A2

An overview of the carbonate variables measured, and methods used by each partner in 2020. White colour indicates discrete samples, while green colour indicates continuous measurements.

Variable	Method and reference	Uncertainty	Institution
C_T (µmol kg^{-1})	SOP2 (Dickson et al., 2007), VINDTA3D (Mintrop et al., 2020)	1.5 µmol kg^{-1}	IMR
C_T (µmol kg^{-1})	SOP2 (Dickson et al., 2007), VINDTA3D (Mintrop et al., 2020)	2.0 µmol kg^{-1}	UiB
C_T (µmol kg^{-1})	SOP2 (Dickson et al., 2007), VINDTA3C (Mintrop et al., 2020)	1.5 µmol kg^{-1}	NIVA
A_T (µmol kg^{-1})	SOP3b (Dickson et al., 2007), VINDTA3S (Mintrop et al., 2020)	1.5 µmol kg^{-1}	IMR
A_T (µmol kg^{-1})	SOP3b (Dickson et al., 2007), VINDTA3S (Mintrop et al., 2020)	2.0 µmol kg^{-1}	UiB
A_T (µmol kg^{-1})	SOP3b (Dickson et al., 2007), VINDTA3C (Mintrop et al., 2020)	1.5 µmol kg^{-1}	NIVA
pH (total scale)	SOP 6b (Dickson et al., 2007; Chierici et al. 1999)	0.003	IMR
pH (total scale)	SOP 6b (Dickson et al., 2007), JASCO spektrofotometer	0.005	UiB
pH (total scale)	SOP 6b (Dickson et al., 2007), HACH DR2800 spectrophotometer	0.005	NIVA
pH (total scale)	Flow through spectrophotometric pH sensor (Reggiani et al., 2016)	0.003	NIVA
pH (total scale)	SAMI-pH sensor (Seidel et al., 2008)	0.003	NORCE
pCO_2 (µatm)	SOP5 (Dickson et al., 2007) w/1 std gas, MApCCO2 system (Sutton et al., 2014)	2.0 µatm	NORCE/ UiB
pCO_2 (µatm)	SOP5 (Dickson et al., 2007), General Oceanics pCO_2 system (Pierrot et al., 2009)	2.0 µatm	NORCE

pCO_2 (µatm)	Membrane equilibrator pCO_2 sensor, SOP5 (Dickson et al., 2007)	5.0 µatm	NIVA

The measured values of C_T and A_T were calibrated against certified reference material (CRM) for quality assurance and as an accuracy check for all data (Certified Reference Material, CRM, Prof. A. Dickson, SIO, USA). To calculate all the carbonate variables including Ω (for calcite and aragonite), the software package CO2SYS has been used (Pierrot et al., 2006; van Heuven et al., 2011). The input variables are primarily A_T and C_T alongside temperature, depth (pressure), salinity, phosphate and silicate, and the output includes in situ pH, pCO_2, Ω calcite and Ω aragonite. At occasions, pH and A_T or pH and C_T have been used as input variables. In the calculations, the carbonic acid constants from Mehrbach et al. (1973), modified by Dickson and Millero (1987), were used (for salinities in the range 0-35 and temperatures in the range 2-35 ^oC). The constant for HSO_4^- from Dickson (1990) (for temperatures of 2-45 ^oC) and in situ temperature and pressure are used when pH is calculated from C_T and A_T. The calcium ion concentration ([Ca_2+]) was assumed to be proportional to the salinity (Mucci, 1983) (for salinities 5-44 and temperatures 5-40 ^oC) and corrected for pressure according to Ingle (1975). Furthermore, the total borate-salinity relationship of Uppström (1974) was used.

Which carbonic acid constants to be used in coastal waters is currently being debated. The large salinity range (0-35) for the carbonic acid constants from Mehrbach et al. (1973), modified by Dickson and Millero (1987), is theoretically determined. However, the constants are not the best for low salinity waters as shown previously, e.g., by Millero (2010). He has suggested more appropriate constants, however, the results by using these are depending on which software is being used (Orr et al., 2015).

Low salinities and, thus, low A_T affect the precision of the measurements, as the A_T analysis instruments (VINDTA3S and 3C) are less precise for such an environment. For this reason, pH has been measured in addition to A_T and C_T at some of the locations with very low A_T and salinity. Furthermore, coastal A_T is influenced by organic and non-carbonic compounds which affect the analysed A_T values. Currently, this is an unsolved matter within the project OA in Norwegian waters. NIVA and IMR have measured pH directly in addition to using calculated pH derived from C_T and A_T by use of the CO2SYS program. The discrete pH measurements were performed at 25°C using the indicator dye meta-cresol purple. UiB measured pH directly on a few of the coastal samples.

Norwegian Environment Agency

Tel.: 73 58 05 00
post@miljodir.no
www.miljødirektoratet.no
Postboks 5672 Torgarden,
7485 Trondheim

Visiting address Trondheim:
Brattørkaia 15, 7010 Trondheim

Visiting address Oslo:
Grensesvingen 7, 0661 Oslo

The Norwegian Environment Agency is a government agency under the Ministry of Climate and Environment. We work towards our vision of a clean and diverse environment. Our primary tasks are to reduce greenhouse gas emissions, manage Norwegian nature, and prevent pollution.

M-2311 | 2022