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Titel | Title

Decadal change of physico-chemical and microbial properties of the North Atlantic Deep Water and adjacent water masses

verfasst von | submitted by

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Abstract

This master thesis investigated the impact of the environmental changes such as warming on the deep ocean. Based on two cruises in the North Atlantic performed in the years 2002 and 2023, the changes in the physico-chemical and microbial parameters of the North East Atlantic Deep Water (NEADW) and adjacent water masses between Iceland and the Azores were investigated. The parameters obtained on these two research cruises were additionally compared with the measurements of the deep-Argo floats deployed in this area from 2014 onwards, but measuring only depth, salinity and oxygen (Argo, 2024). All physical and chemical parameters significantly changed. While the increase in temperature in the NEADW was not statistically significant, the increase in temperature in the Iceland-Scotland-Overflow-Water (ISOW) and the Labrador-Sea-Water (LSW) was significant over these 21 years. The freshening of the NEADW and the reduction in the oxygen was clearly detectable across the stretch of the transect. The decrease in the concentration of inorganic nutrients and dissolved organic carbon in the deep-water masses of the North Atlantic suggests a reduction of the biological pump efficiency between 2022 and 2023 as indicated also by the concomitant decrease in heterotrophic microbial abundance.

Keywords: NEADW, decadal changes, physico-chemical and microbial parameters, global warming

Zusammenfassung

Diese Masterarbeit untersucht die Auswirkungen der Veränderungen in der Umwelt, wie die globale Erwärmung auf die Tiefsee. Basierend auf zwei Fahrten im Nordatlantik im Abstand von 21 Jahren wurden die Veränderungen der physikalisch-chemischen und biologischen Parameter der Tiefsee basierend auf dem Nordostatlantischen Tiefenwasser (NEADW) zwischen Island und den Azoren und der wichtigsten, dem NEADW angrenzenden Wassermassen analysiert. Die Ergebnisse wurden zusätzlich mit den Messungen der deep Argo-Floats verglichen, die ab 2014 in dem Gebiet eingesetzt wurden, aber nur Tiefe, Salzgehalt und Sauerstoff messen.
Alle physikalischen und chemischen Parameter veränderten sich signifikant, was zu einer reduzierten mikrobiellen Abundanz zwischen 2002 und 2023 führte. Die Temperaturänderungen im NEADW waren statistisch nicht signifikant, aber bereits Iceland-Scotland-Overflow-Water (ISOW) und im Labrador-Seawater (LSW) war die Temperaturerhöhung über diese 21 Jahre signifikant. Die Verringerung des Salzgehalts des NEADW und der Sauerstoffversorgung waren über den gesamten Abschnitt des Transekts deutlich sichtbar. Die reduzierte Menge an Nährstoffen sowie der abnehmende Anteil an organischem Kohlenstoff (DOC) führt zu der Annahme einer Reduktion der Wirkungsweise der biologischen Pumpe im Nordatlantik.

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Introduction

The North Atlantic is the region where the main driver of the thermohaline circulation is formed – the North Atlantic Deep Water (NADW), a conveyor-belt like current covering all ocean basins within 1000+ years (Tomczak & Godfrey, 1994). The NADW (consisting of a western and an eastern branch in the North Atlantic) occurs mainly between 1500 and 4000 m depth flowing to the south above the Antarctic Bottom Water (AABW) flowing to the north (Van Aken, 2007).

The thermohaline or meridional ocean circulation connects all the oceanic basins over a time scale of 800-1500 years and is mainly driven by the North Atlantic Deep Water (NADW) formed in the Greenland-Iceland-Norwegian Sea (Van Aken, 2007)(Fig. 1). On its flow towards south of 60°N several water masses contribute to the Northeast Atlantic Deep Water (NEADW) such as the Labrador Sea Water (LSW), Iceland-Scotland Overflow Water (ISOW) and the Lower Deep water (LDW) (van Aken, 2007; Reinthaler et al., 2010). Fig. 1 shows the major water masses forming the NEADW. In the present study, also these water masses and their development were included, as far as covered by the research cruises Transat 1 in 2002 and DEPOCA in 2023 (Fig. 2).

Currently available environmental, chemical and biological data for water masses below 2000 m depth are scarce. Cheng et al. (2022) described the impact of anthropogenic greenhouse gas concentrations on the heat absorption by the oceans and its redistribution processes in the deep ocean. While the about 4000 Argo floats currently deployed in the global ocean record various physical and chemical parameters of the water column between the surface and 2000 m, deep Argo floats reaching deeper than 2000 m only provide temperature, salinity and O_2 data. They are only in place since the year 2014.

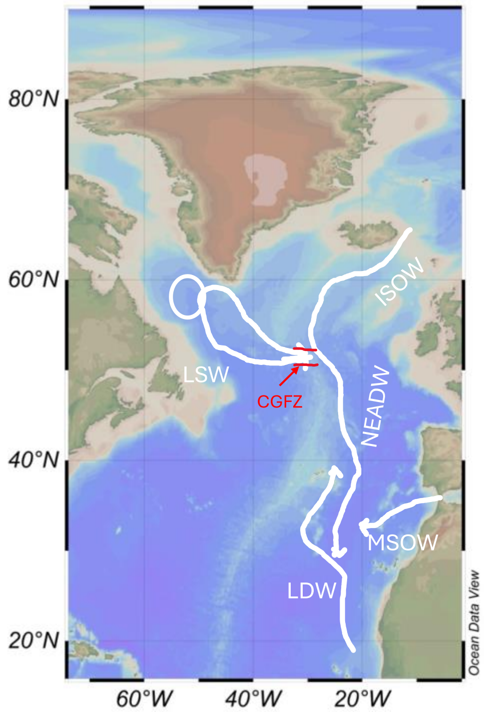

Figure 1: Simplified flow pattern of water masses in the deep northern North Atlantic *after Reinthaler, 2010.* ISOW-– Iceland Scotland Overflow Water, LDW- Lower Deep Water, LSW- Labrador Seawater, NEADW-North East Atlantic Deep Water, CGFZ – Charlie-Gibbs Fraction Zone.

Increased frequencies of marine heat waves have been reported for essentially all oceanic basins over the past few years (Scannell et al., 2016). Also, warming of the mesopelagic waters have been documented ; Cheng et al., 2022). An analysis of the variability of the LSW over the past decades revealed a significant increased in temperature using Argo data (Kieke & Yashayaev, 2015). However, how this warming reported for mesopelagic waters has already propagated into the bathypelagic waters has not been investigated yet.

The Greenland-Iceland-Norwegian (GIN) Sea is the major site of deep-water formation in the North Atlantic (Tomczak & Godfrey, 1994). The extent of deep water formation depends on the cooling of the Gulf Stream and the extent of sea ice, the latter increasing the salinity of the water mass and in connection with the cooling of the surface water mass increases the density of the seawater (Yang et al., 2016). Sea ice consistently retreats in the Arctic Sea over the past few decades(Cavalieri & Parkinson, 2012) and increased runoff from glacier melting leads to a freshing of the surface waters resulting in a slow down of deep water formation in the GIN Sea(Love et al., 2021). Hence, one can hypothesize a freshening of deep water in the northern region of the North Atlantic. This might also impact the chemical and biological activity on the deep waters.

Meso- and bathypelagic organisms are depending on the organic matter supplied by surface water primary production(Lima et al., 2014). Thus, life in the deep ocean depends on the supply of particulate (POM) and dissolved organic matter (DOM) transported into the deep waters via sedimentation and downwelling, respectively (Burd et al., 2010). The biological pump ensures the vertical flux of POM to the meso- and bathypelagic water column where the biota are utilizing this organic matter and remineralizing a major fraction of the organic carbon to CO_2. Hence, the extent of the biological pump determines the transfer efficiency of organic carbon from the surface waters into the ocean's interior and serves as important climate factor as high primary production leads to a drawdown of CO_2 from the atmosphere into the surface ocean(Nowicki et al., 2024). As the deep Argo floats do not collect information beyond the hydrographical data, there is limited information available about the microbial life in the deep ocean. The main source of information on microbial life is obtained from cruises and samples taken at individual stations and depths.

This thesis compares the results of the two research cruises to investigate whether potential changes in the physico-chemical parameters also lead to changes in the microbial abundance and activity in the bathypelagic waters of the North Atlantic. Thus, the main objective of this work was to determine whether there is an impact of global warming on the physico-chemical and microbiological parameters detectable in the Northeast Atlantic Deep Water and adjacent water masses over the last 21 years in the North Atlantic.

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Material and Methods

Sampling locations

Seawater samples were collected in the North Atlantic between Iceland and the Azores in the years 2002 during the Transat 1 cruise and DEPOCA (2023) by members of the Microbial Oceanography Group of the University of Vienna with R/V *Pelagia* (Fig. 2). The data collected during these cruises were analyzed and compared to detect possible trends over these two decades. The focus was on the water masses below 2000 m and especially on the North East Atlantic Deep Water (NEADW).

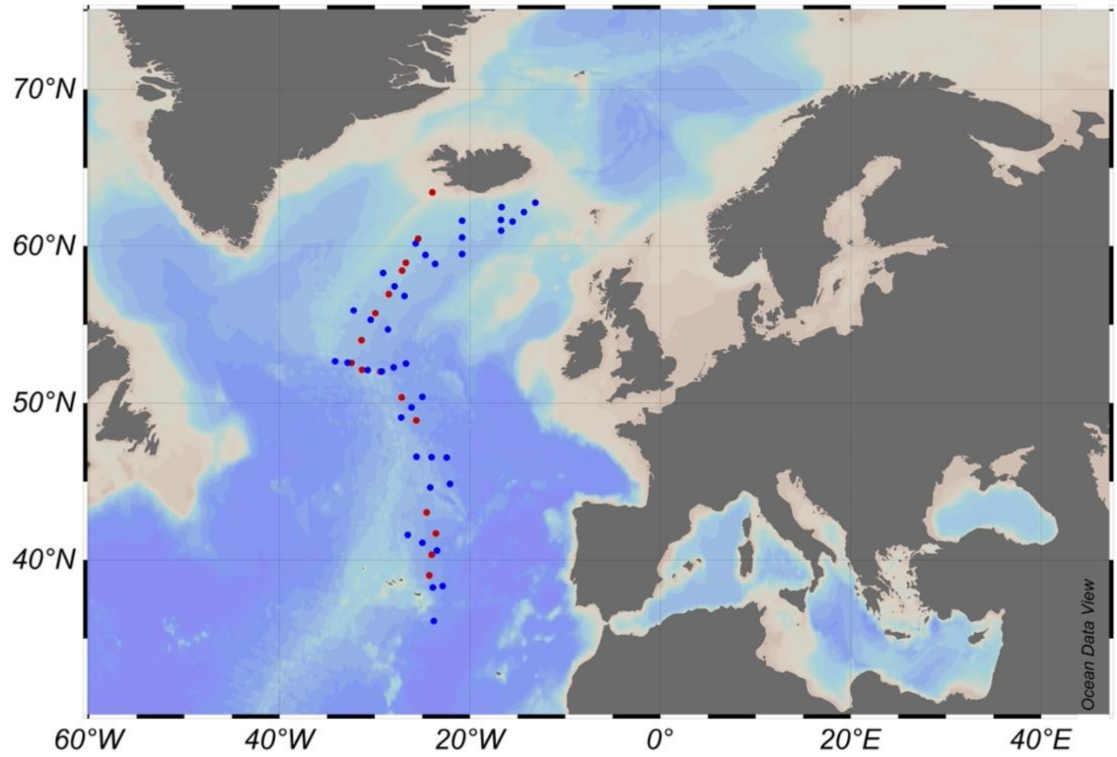


Figure 2: Stations of Transat1 (blue dots) and DEPOCA (red dots) where seawater samples were collected

The two cruises were conducted in the eastern basin of the North Atlantic spanning a transect from 63°N to 39°N with RV *Pelagia*. The Transat 1 cruise was performed in the summer of 2002 and the DEPOCA cruise in the summer of 2023. Only stations in the latitudinal range covered by both cruises were included in the analyses. The stretch was split into three sections along the transect:

1 North of the CGFZ (Charlie-Gibbs-Fraction Zone): > 52.6°N
2 Around the CGFZ: between 52°N and 52.6°N
3 South of the CGFZ: < 52°N

The decision for splitting up the regions was based on the factors that north of the CGFZ is the formation of the NEADW; the CGFZ brings water from west of the mid-Atlantic ridge. South of the CGFZ the water masses are more stable until the impact of the Mediterranean Overflow Water, which is not part of the range covered (Fig. 3). Furthermore, the waters of the northern region of the NEADW are substantially younger than the once further south (Van Aken, 2000).

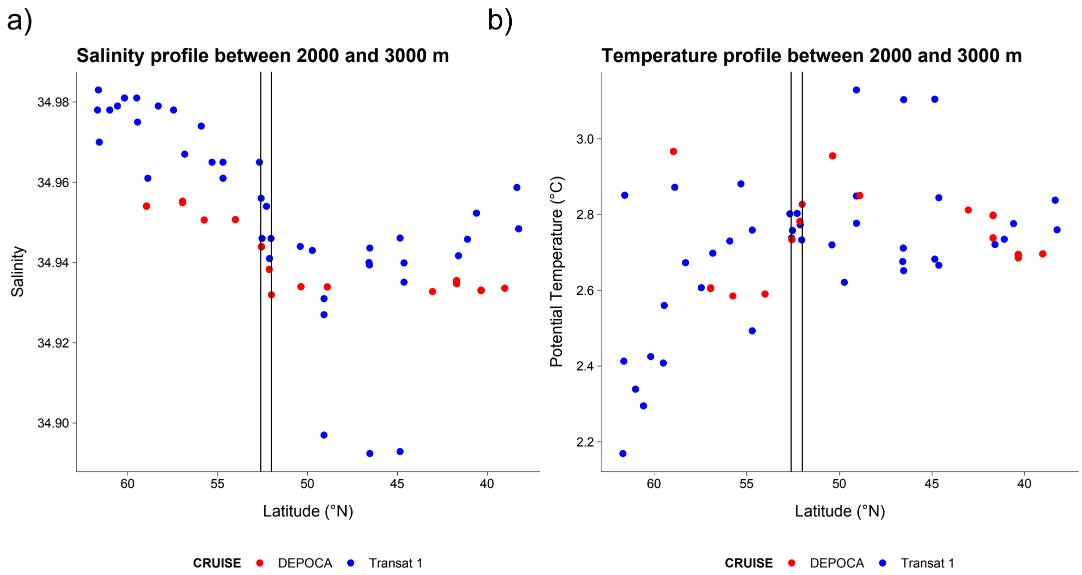


Figure 3: Gradients of salinity (a) and potential temperature (b). Vertical lines indicate the area of the CGFZ.

There is no seasonal impact assumed, as the cruises were in the same season (late summer). This was also cross-checked and confirmed with the Deep-Argo data for the timeframe available.

Water Mass Analysis

The definition of the water masses followed the salinity and temperature characteristics of the major water masses as defined in van Aken (2000).

The results of the CTD downcasts in in both research cruises were used. For Transat 1 all sensors were calibrated, for DEPOCA only O_2 sensors were calibrated on board, the other sensors were calibrated by manufacturers' tables. All sensors were rinsed after each sampling.

The conversion from dbar to meters was done with the features of ODV using formulas based on accepted methods. Also, the salinity and oxygen data of the deep-Argo floats were analyzed. The floats in the area and ±1° off the sampling stations were considered for the comparison.

Nutrient measurements

The concentrations of NO_3 and PO_4 were analyzed directly on board of RV *Pelagia* after collection. They were gently filtered through 0.2 µm Acrodisc filters. A sequential flow analysis with a Technicon TRAACS 800 was performed.

Data Processing

All data from the two cruises were analyzed with Excel for Mac Version 16.86, ODV version 5.7.1 and 'R' Version 2024.04.1+748 on a Mac under MacOS 12.7 and higher. Most of the parameters were not normally distributed, so in these cases the Mann-Whitney U Test was applied, otherwise a linear model used.

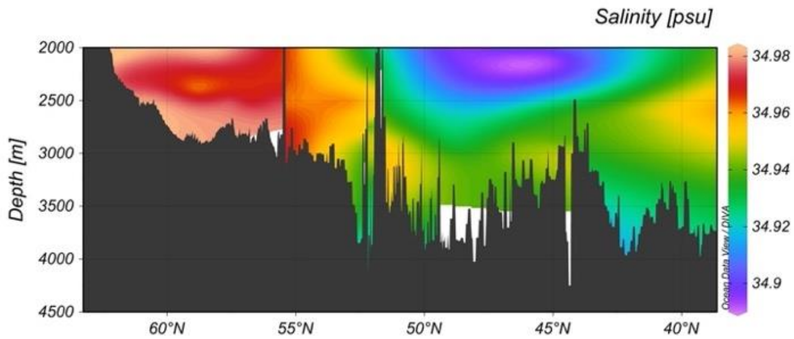
Results

Physical characteristics

Salinity

The salinity profiles indicated a decrease in salinity specifically in the bathypelagic waters of the northern North Atlantic (north of 52°N) between the year 2002 (Transat 1 cruise) and 2023 (DEPOCA cruise) less-saline waters also in the deep ocean. The profiles for the two cruises are shown in Fig. 4.

Transat



DEPOCA

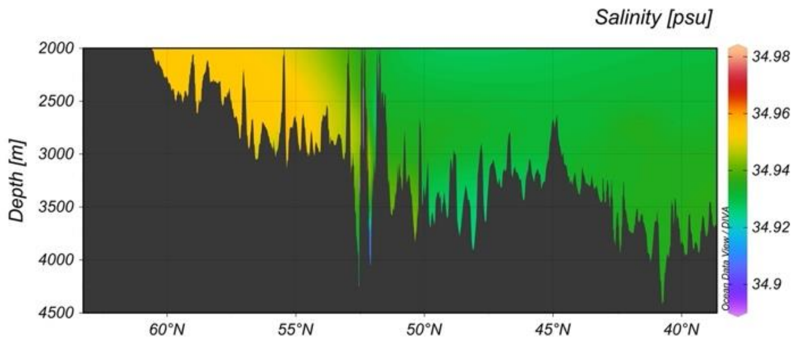


Figure 4: Salinity profile (generated by ODV) of the waters between 2000 and 4500m for Transat 1 (upper panel) and DEPOCA (lower panel).

At the depth range between 2400 and 3000, salinity in 2023 was well below the salinity values of 2002 (Fig. 5) in all three sections (north of, around, and south of the CGFZ). Around the CGFZ, the difference between the years was smallest due to the broad range of values. It is assumed that the mixing effect between west and east of the Mid-Atlantic ridge is partly of the large variability. For the NEADW a comparison between the two cruises over a timespan of 21 years showed a significant decrease in salinity. While the results of the stations occupied in 2002 demonstrated a great variability, the levels in 2023 were significantly lower than in 2002 (Mann-Whitney U Test: U(n1=22,n2=29)=96, z=4.232, p<.001, r=.593).

a)

b)

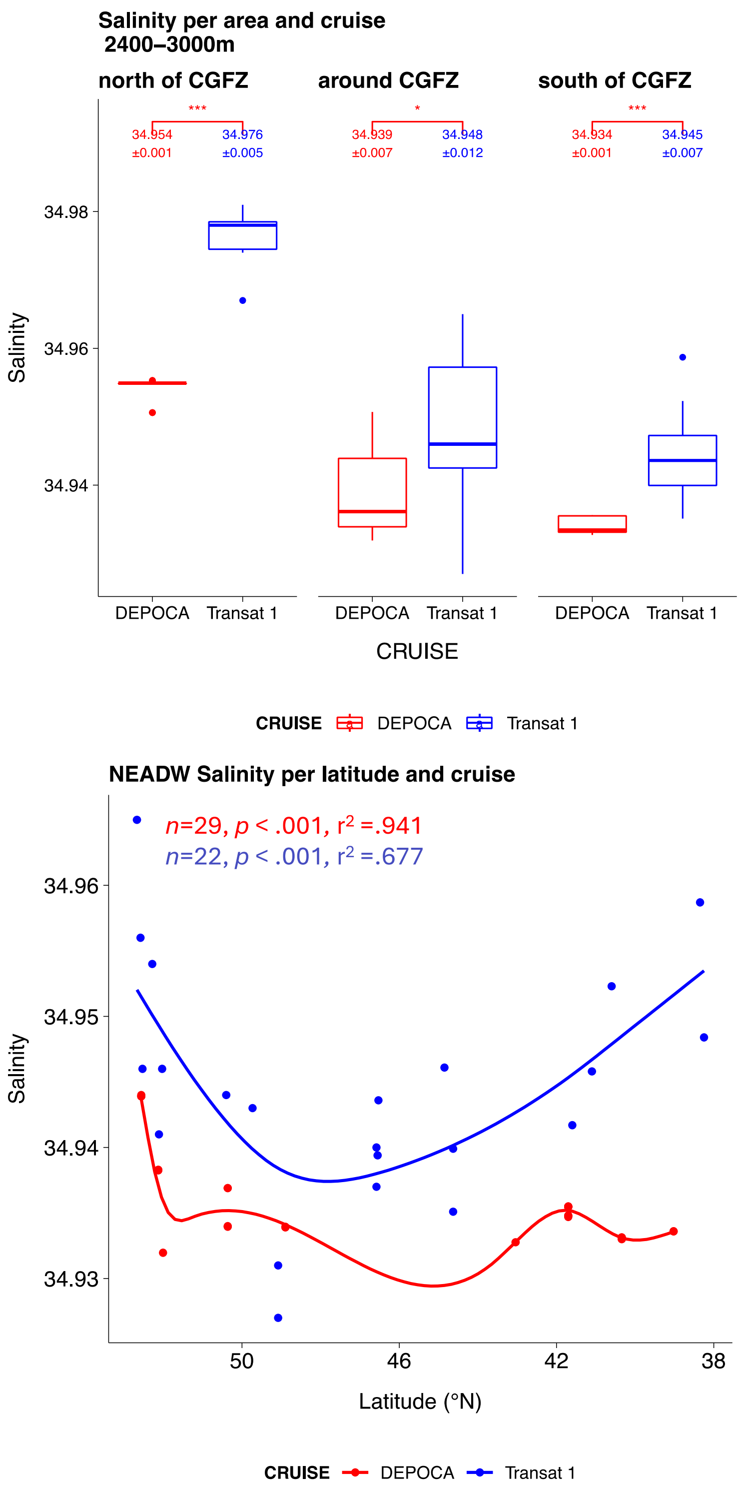


*Figure 5: Salinity distribution across areas (a). Salinity across the latitudes within the NEADW (b). In (a) the significance level is indicated with * P<0.05, *** P<0.001. The curve reflects the generalized additive model ("gam") with the formula = y ~ s(x, bs = "cs"), as supplied as default by R's geom_smooth() function.*

An analysis of the deep Argo floats in the core NEADW between 2500 and 2800 m deployed in this area from the year 2014 onwards confirmed the trend especially for the area north and around the CGFZ, while for the region further south, there are only few samples with a gap between 2014 and 2021 when considering only floats around ± 1° off the stations sampled during the research cruises (Fig. 6).

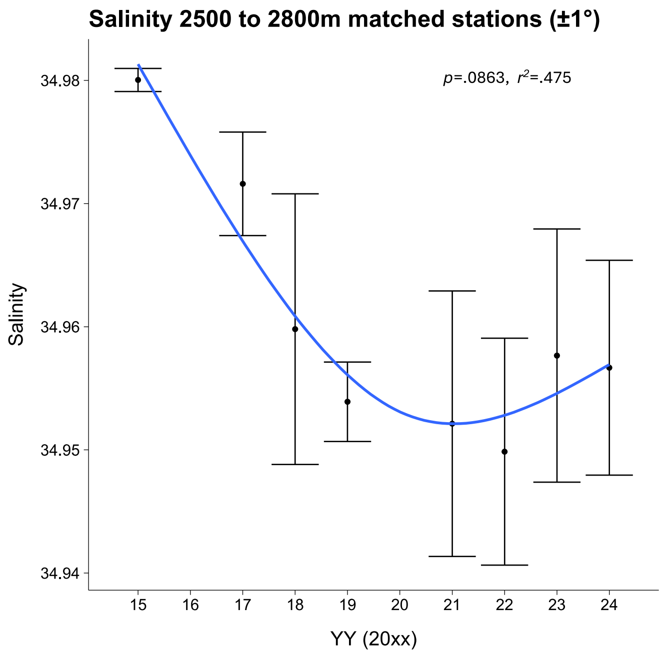
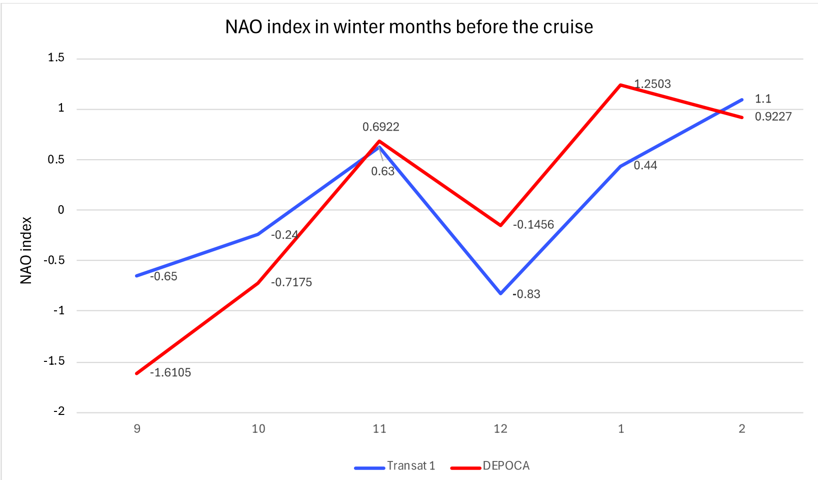


Figure 6: Deep-Argo floats in the area of the stations (± 1° deviation from the sampling location). The curve reflects the generalized additive model ("gam") with the formula = y ~ s(x, bs = "cs"), as supplied as default by R's geom_smooth() function.

The NAO (North Atlantic Oscillation) is the difference between the Iceland low and the Azores high pressure system (*State of the Global Climate 2023*, 2024). It is expressed as index which is especially in the winter months important for the deep-water formation Fig. 7a shows the tendency of the NAO index of the relevant winter seasons prior to the cruises as well as the index averaged for the 5 preceding winters (Fig. 7b). Comparing Fig. 7a and Fig. 7b, the NAO index does not explain the observed trend.

a)



b)

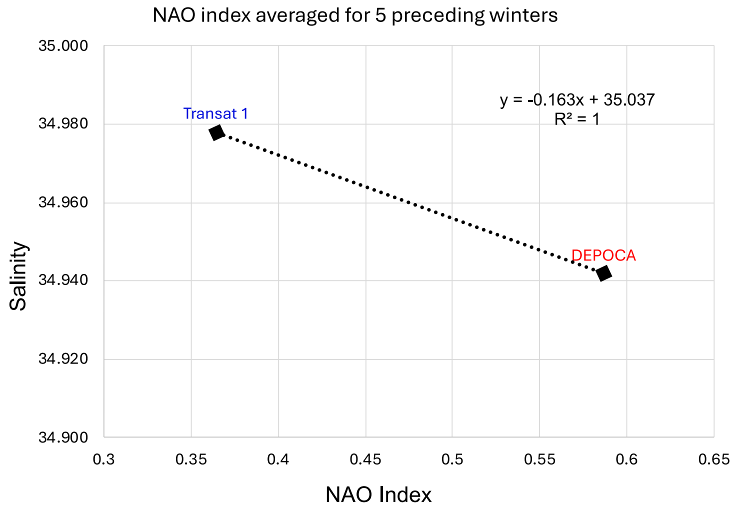
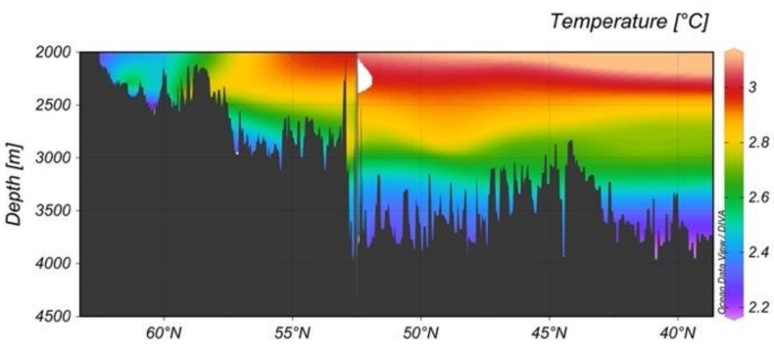


Figure 7: NAO index in the winter season prior to the cruises. Numbers along the x-axis reflects calendar months (a). Average indices of 5 preceding winters (b).

Potential temperature

Overall, the potential temperature increased in the deep sea from the year 2002 to 2023 but not significantly (Fig. 8). The profiles indicate a warm spot around the CGFZ and north of 58°N in 2023.

Transat 1



DEPOCA

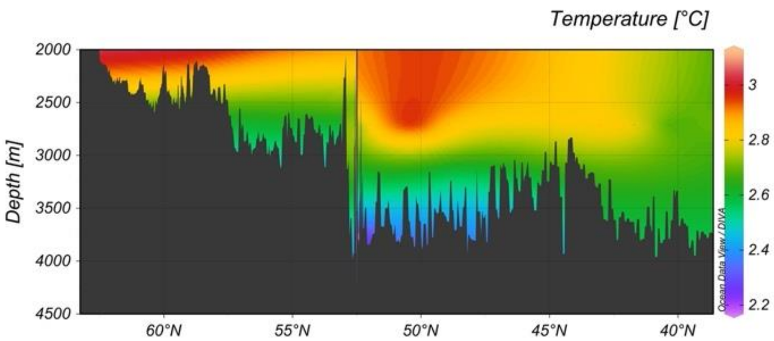
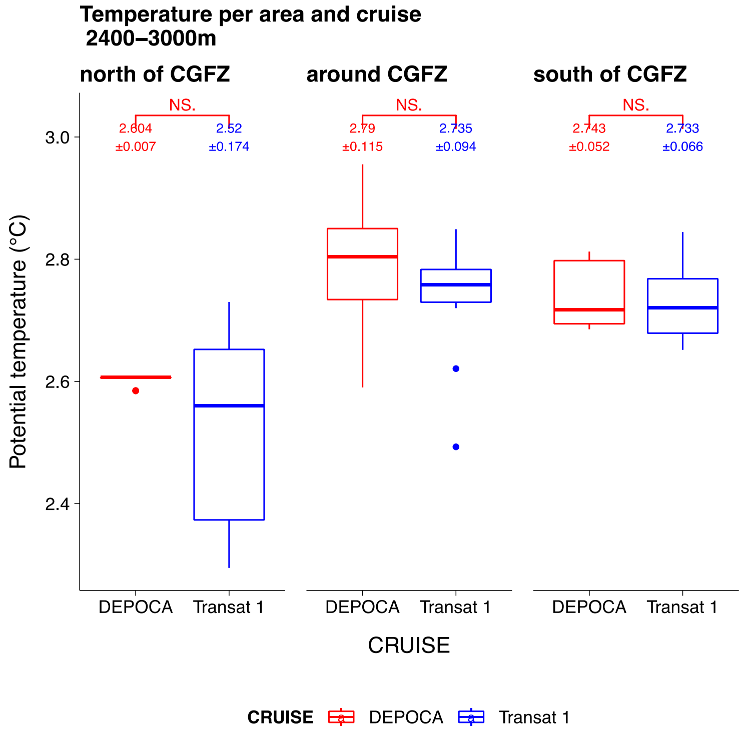


Figure 8: Potential temperature below 2000m at Transat 1 and DEPOCA.

The potential temperature in the three sections at the depth range of 2400 to 3000m revealed a non-significant increase in the northern section and around the CGFZ, while south of the CGFZ potential temperature in 2023 was in the same range as in 2002, even slightly lower (Fig. 9a). Fig. 9b shows the potential temperature measured during the two cruises with outliers around the CGFZ. The overall temperature profile did not change significantly, U(n1=22, n2=29)=362, *z*=-.808, *p*=.419, *r*=.113). The two outliers of the DEPOCA are from the same station at 50.3°N in different depths (2710 and 3144 m).

a)



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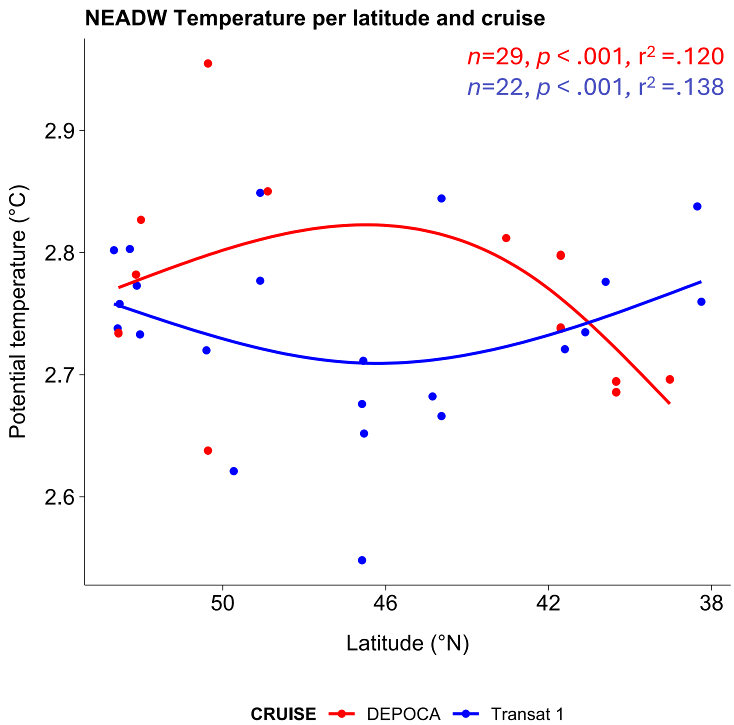


Figure 9: Comparison of potential temperature per area, the significance level is indicated with NS = not significant. (a), potential temperature in NEADW (b). The curve reflects the generalized additive model ("gam") with the formula = y ~ s(x, bs = "cs"), as supplied by default by R's geom_smooth() function.

The temperature-salinity plot below 1000m (Fig. 10) shows the expected curve in the zone of low temperature and salinity. Focusing on the NEADW (Fig. 11) there was a clear trend to a lower salinity in 2023 as compared to 2002 (n= 63, p<.001, r^2=.412).

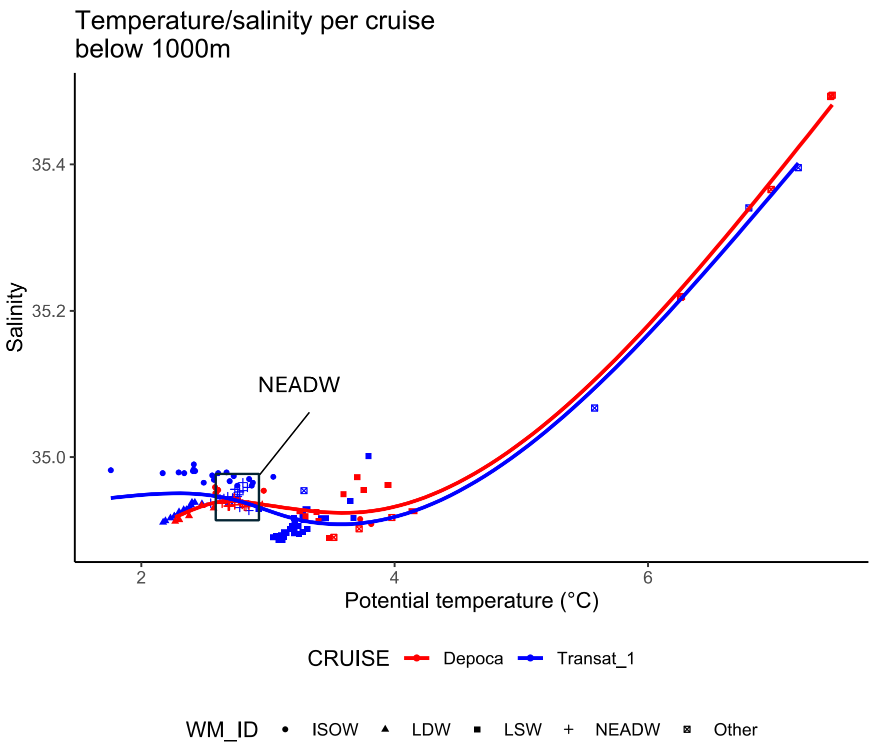


Figure 10: Potential temperature-salinity plot of the water masses below 1000m (a) and of the NEADW (b). WM_ID – ISOW – Iceland Scotland Overflow Water, LDW- Lower Deep Water, LSW- Labrador Seawater, NEADW- North East Atlantic Deep Water

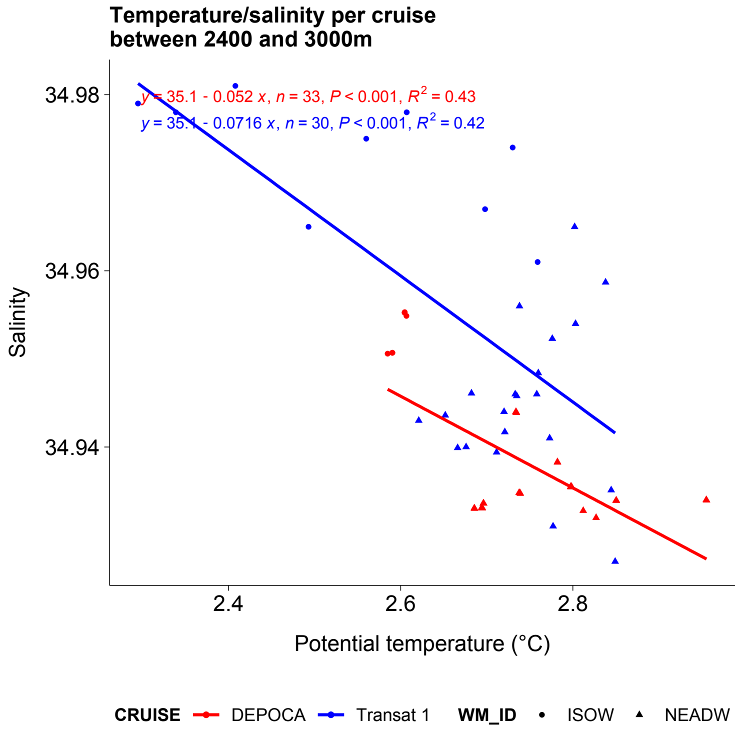
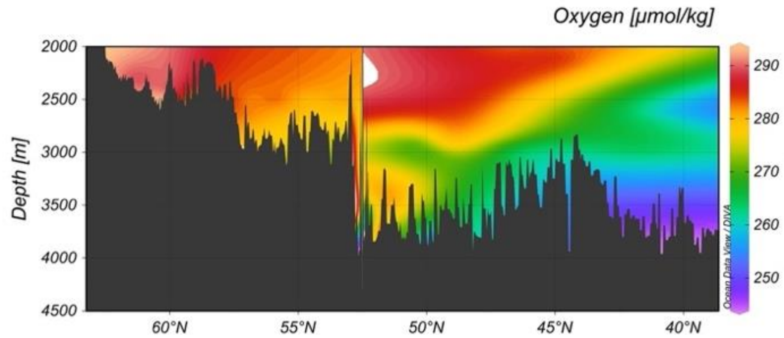


Figure 11 :Potential temperature-salinity distribution of the two research cruises between 2400 and 3000m depth

Oxygen

The comparison of the two cruises indicated overall a significant decrease in oxygen concentration from the north to the south (Fig. 12).

Transat 1



DEPOCA

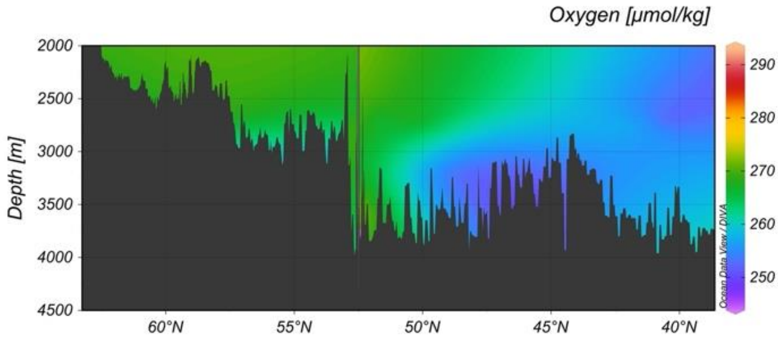
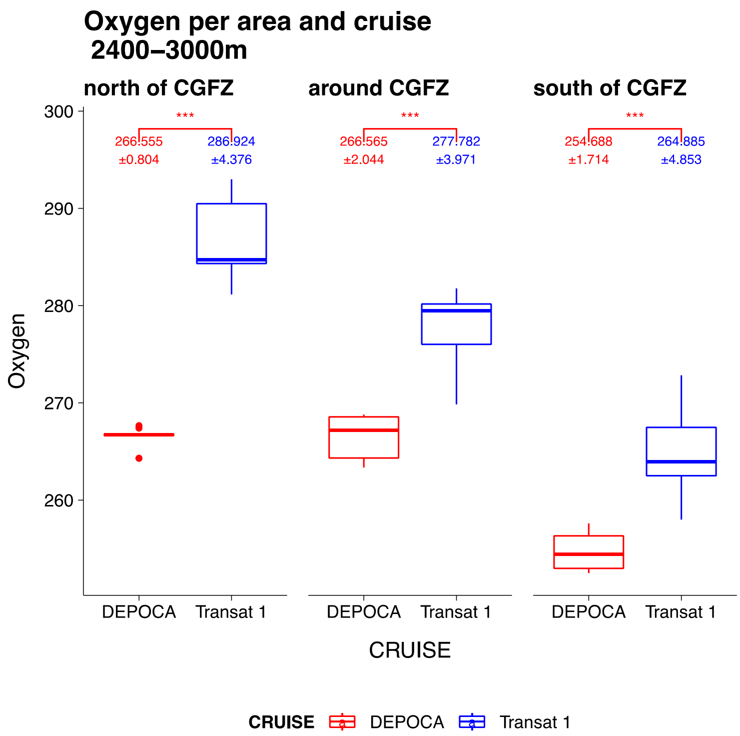


Figure 12: Oxygen concentrations below 2000m during Transat 1 and DEPOCA

a)



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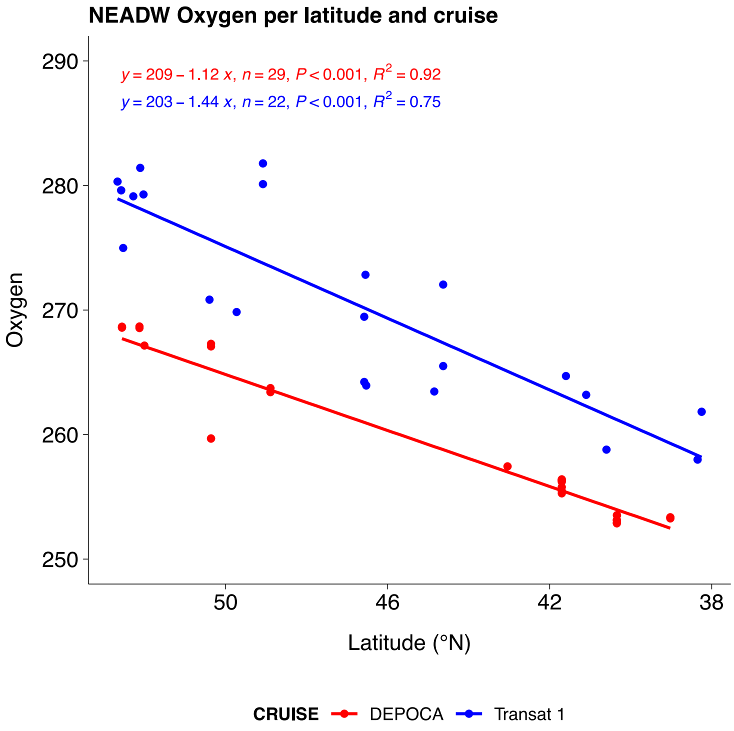


Figure 13: Oxygen concentration (in µmol kg^{-1}) per area, the significance level is indicated with *** P<0.001. (a). NEADW per latitude over the whole transect (b).

There was a significant decrease in oxygen concentration in all three regions (Fig. 13a). Fig. 13b shows the declining latitudinal oxygen concentration in the NEADW for the years 2002 and 2023. The difference between the years 2002 and 2023 is significant, U($n1$=22, $n2$=29)=85, z=-4.441, p<.001, r= .622).
The Deep-Argo data support the results for the period of their deployment (Fig.14). However, the Deep-Argo data indicated seasonally small, albeit not significant changes in oxygen concentrations (Fig.15). As the cruise data are of the same season (August, September), there is likely no seasonal impact on the data.

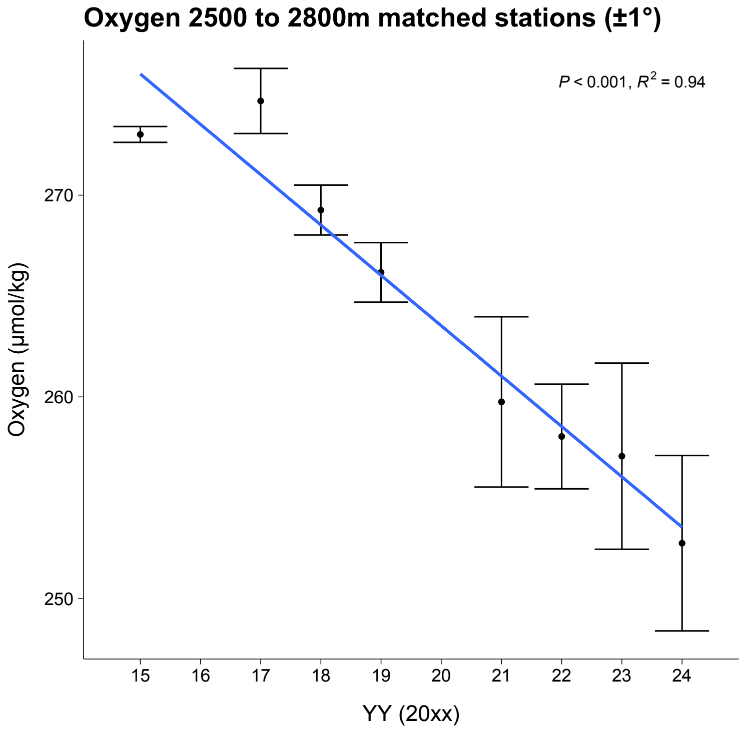


Figure 14: Deep Argo oxygen concentrations in the area over the years 2015-2024

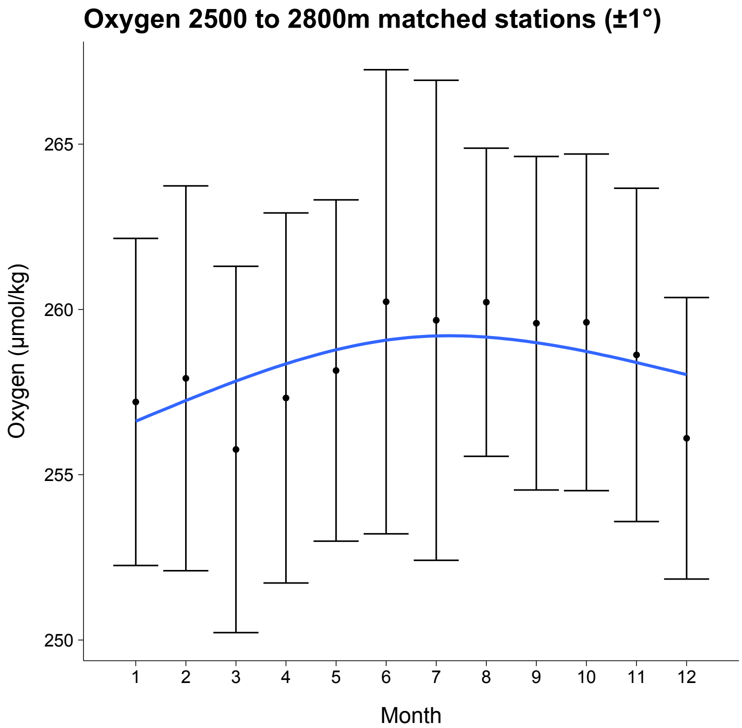


Figure 15: Monthly development in oxygen concentrations over the period 2015 to 2023. Dots indicate the monthly average of Argo profiles, vertical bars represent the standard deviation.

Summary of abiotic parameters

Table 1 includes the main water masses adjacent to the NEADW. There was a clear increase in average temperature in the ISOW of 14.6% and of 16.1% in LSW from 2002 to 2023, while it was only around 0.8% in the NEADW and around 2% in the LDW. In these water masses, the oxygen content decreased by 6.2 to 7%.

Table 1: Physical characteristics of the various water masses and the areas

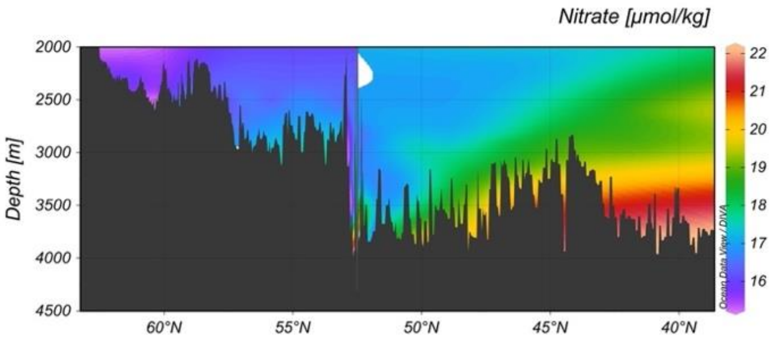
Watermass Cruise	DEPTH (m)	Salinity	Oxygen (µmol kg-1)	Temperature (°C)
north of CGFZ				
ISOW				
DEPOCA	2,133 +/- 572	34.942 +/- .019	269.08 +/- 3.14	2.970 +/- .485
Transat 1	2,294 +/- 467	34.978 +/- .018	286.90 +/- 5.27	2.591 +/- .345
LSW				
DEPOCA	1,514 +/- 425	34.919 +/- .016	270.69 +/- 7.48	3.522 +/- .421
Transat 1	1,654 +/- 184	34.907 +/- .014	288.13 +/- 3.61	3.301 +/- .178
around CGFZ				
LDW				
DEPOCA	3,751 +/- 131	34.918 +/- .007	269.44 +/- 2.03	2.342 +/- .073
Transat 1	3,595 +/- 174	34.933 +/- .005	272.54 +/- 11.65	2.372 +/- .046
LSW				
DEPOCA	1,776 +/-	34.919 +/- .000	271.45 +/- .04	3.295 +/- .000
Transat 1	1,769 +/- 141	34.895 +/- .017	287.37 +/- 2.71	3.060 +/- .069
NEADW				
DEPOCA	2,708 +/-	34.940 +/- .005	268.37 +/- .60	2.766 +/- .038
Transat 1	2,706 +/- 168	34.951 +/- .009	279.12 +/- 2.19	2.768 +/- .030
south of CGFZ				
LDW				
DEPOCA	3,198 +++	34.930 +++	253.98 +++	2.571 +++
Transat 1	3,859 +/- 349	34.921 +/- .008	248.45 +/- 5.76	2.291 +/- .096
LSW				
DEPOCA	1,599 +/- 323	34.948 +/- .018	262.08 +/- 1.37	3.916 +/- .201
Transat 1	1,974 +/- 66	34.912 +/- .030	281.29 +/- 5.86	3.229 +/- .186
NEADW				
DEPOCA	2,749 +/- 125	34.934 +/- .001	257.05 +/- 4.43	2.758 +/- .088
Transat 1	2,852 +/- 175	34.942 +/- .008	267.53 +/- 6.83	2.724 +/- .083

Inorganic nutrients

Nitrate

As usual, nitrate was the most abundant form of nitrogen in the deep sea (Fig. 16). The concentration of nitrate was lower in the deep waters at around 40°N in 2023 than in 2002 (Fig. 16). Overall, however, the nitrate concentrations were not significantly different in the waters from 2000 and 4000 m depth between 2002 and 2023 ($n=32$, $p=.6372$, $r^2=-.256$), increasing with decreasing latitudes (Fig. 17).

Transat 1



DEPOCA

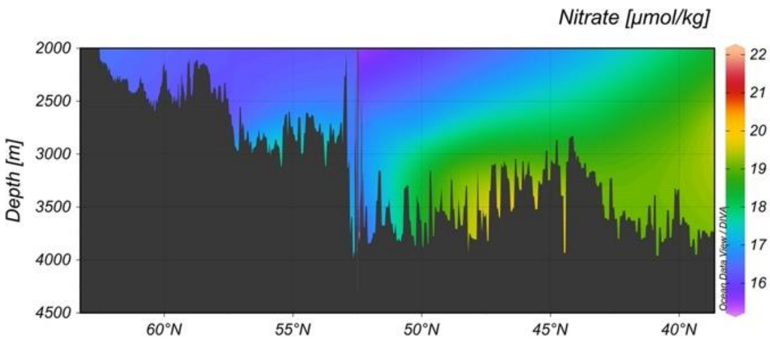


Figure 16: Distribution of nitrate below 2000m depth

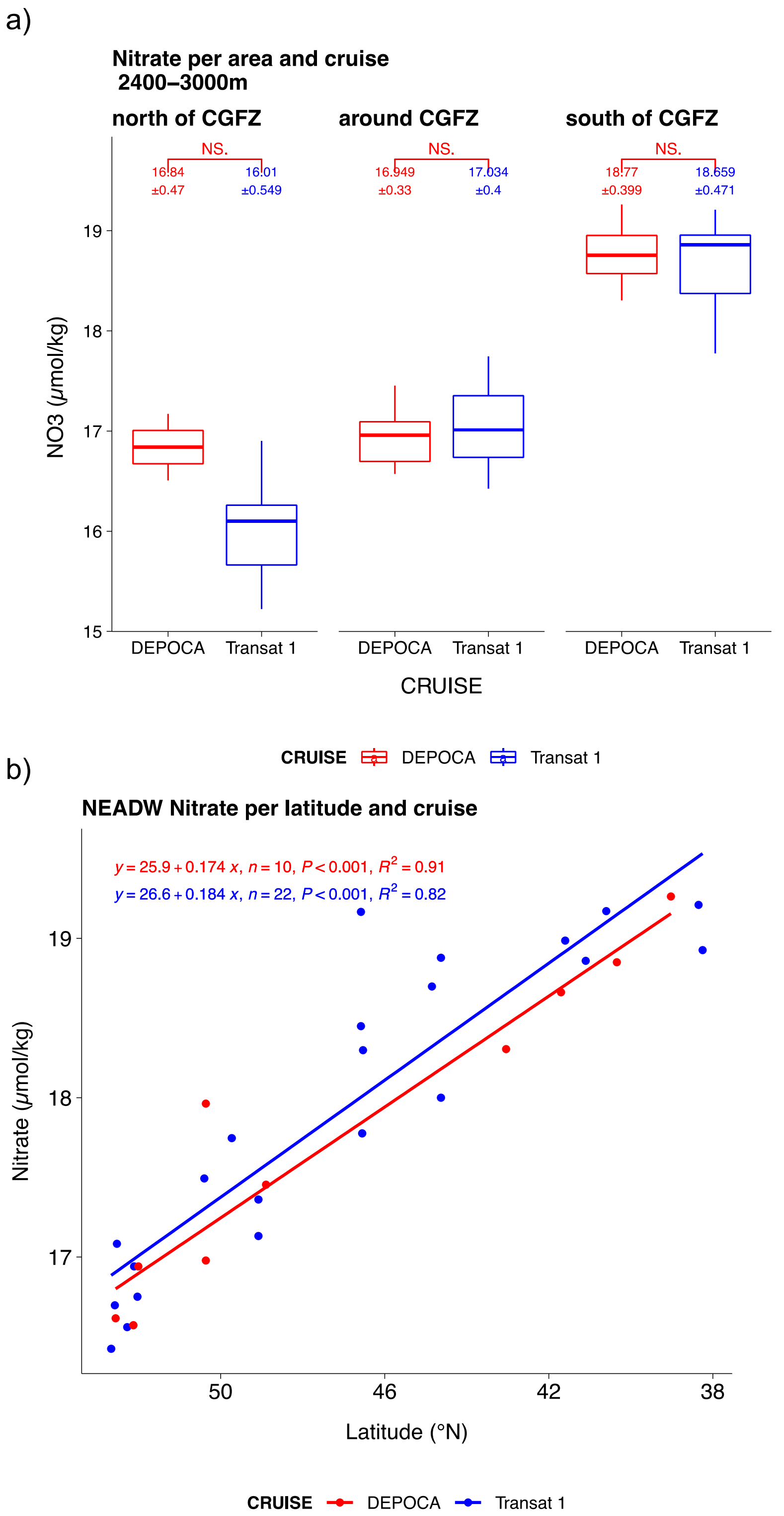
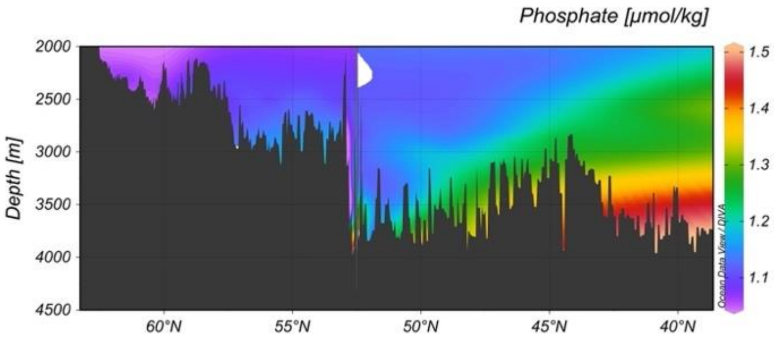


Figure 17: Comparison of nitrate concentrations per area, the significance level is indicated with NS = not significant. (a) and in the NEADW across the latitudinal transect (b).

Phosphate

Phosphate concentrations were higher, albeit not significantly (n=32, p=0.1543, r^2=-.035) in the year 2002 (Transat1) vs. 2023 (DEPOCA); (Fig. 18, Fig. 19).

Transat1



DEPOCA

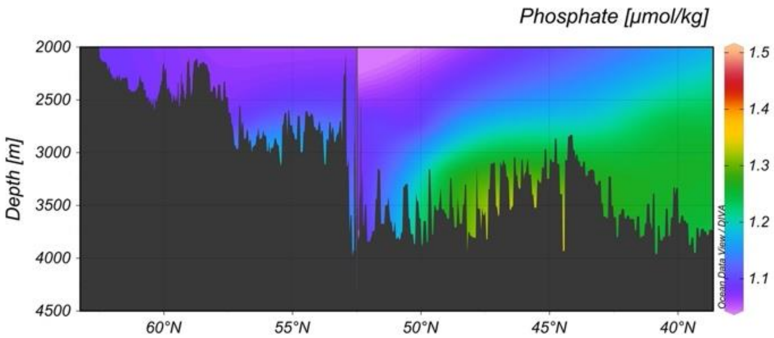


Figure 18: Profile of phosphate below 2000 m depth

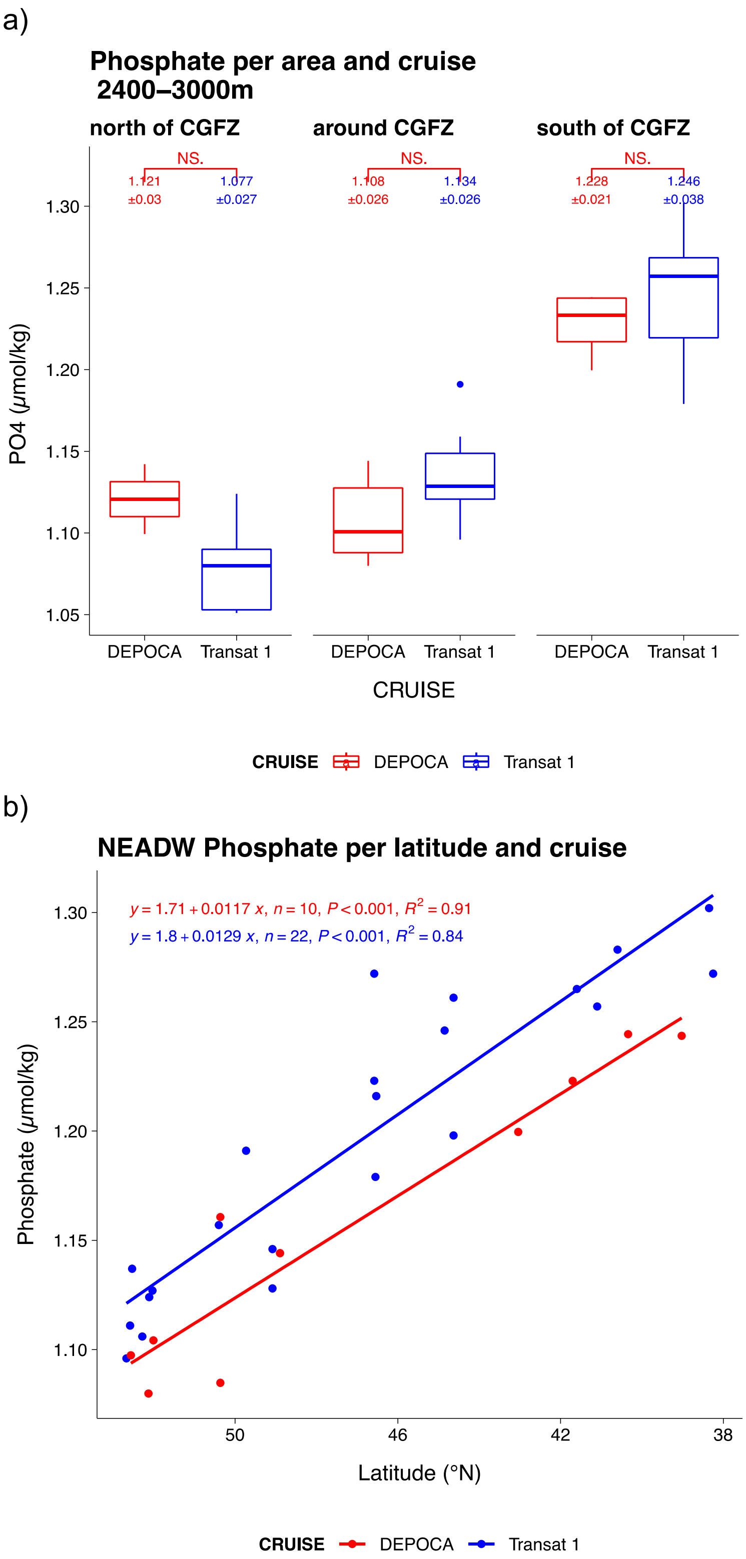
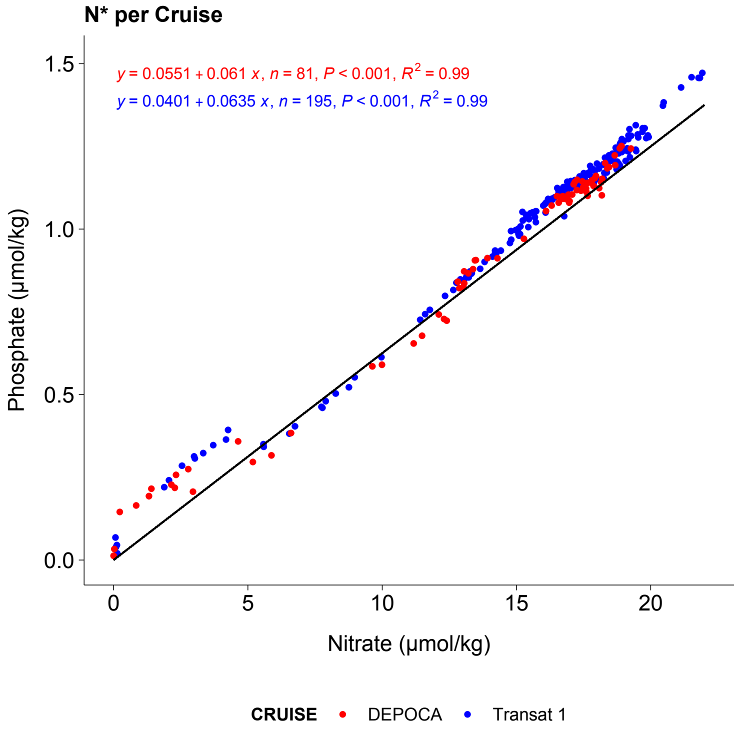


Figure 19: Comparison of phosphate concentrations per area, the significance level is indicated with NS-not significant. (a) and in the NEADW across the latitudinal transect (b)

*N**

N* indicates the deviation from the Redfield ratio between phosphate and inorganic nitrogen (1:16). Fig. 20 shows that at both research cruises the phosphate concentrations were mostly higher along the transect (Fig. 20a) as well as in the NEADW (Fig. 20b) than predicted by the Redfield ratio.

a)



b)

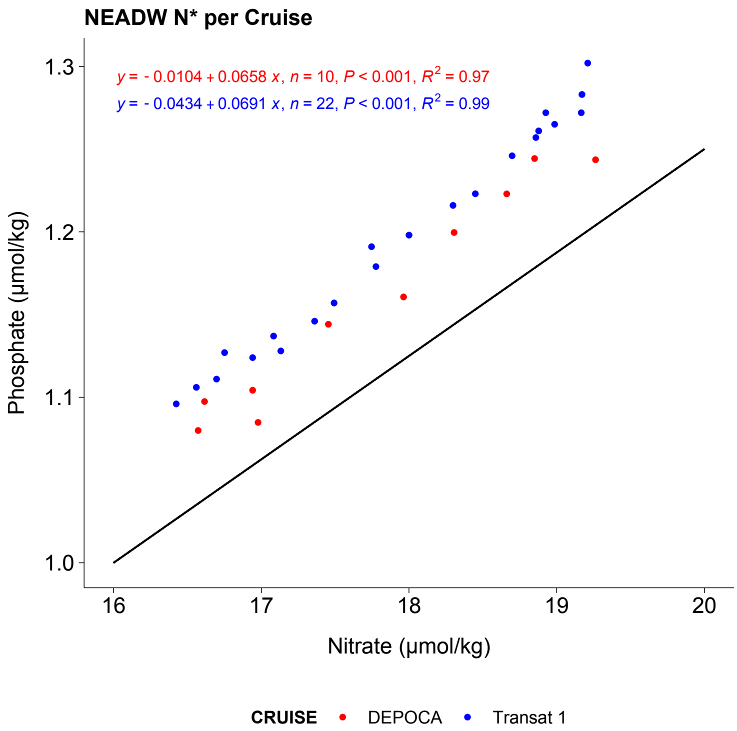
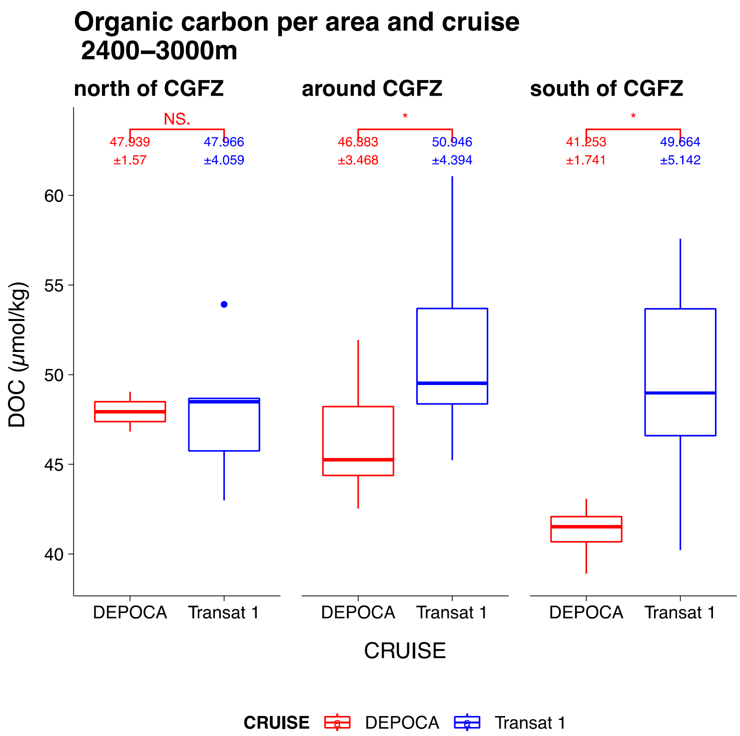


Figure 20: Relation between nitrate and phosphate concentrations over the whole water column (a) and the NEADW (b). The black line indicates the Redfield ratio of inorganic nitrogen to phosphate of 16:1

Dissolved organic carbon (DOC)

Dissolved organic carbon concentrations were generally lower in the NEADW in the year 2023 (DEPOCA) than in 2002 (Transat 1) (Fig. 21). While in the northern region of the North Atlantic the differences in the DOC concentrations were not significantly different (Fig. 21a), these differences were significant at the two lower latitudinal regions.

a)



b)

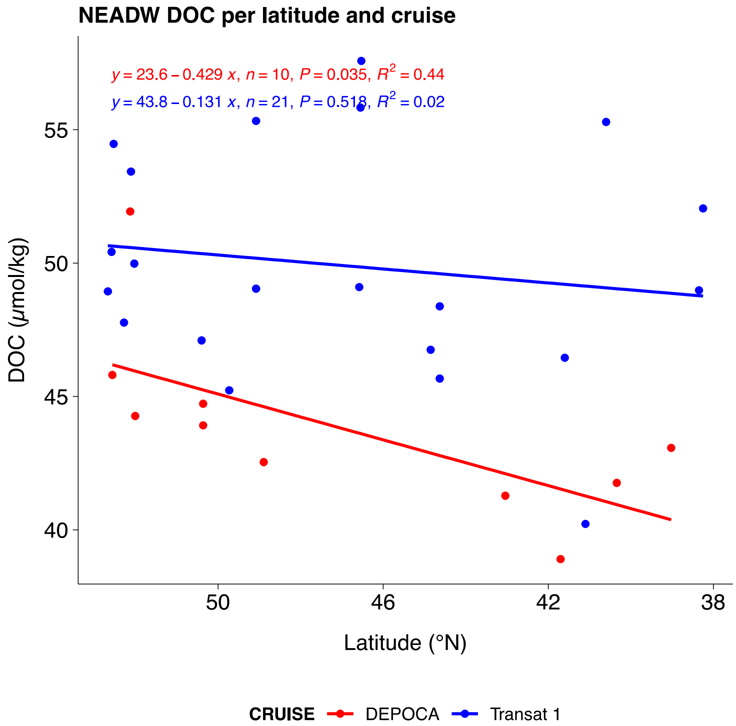


Figure 21: DOC concentrations per area, the significance levels are given: * indicates P<0.1, NS = not significant (a) and for NEADW along the transect (b)

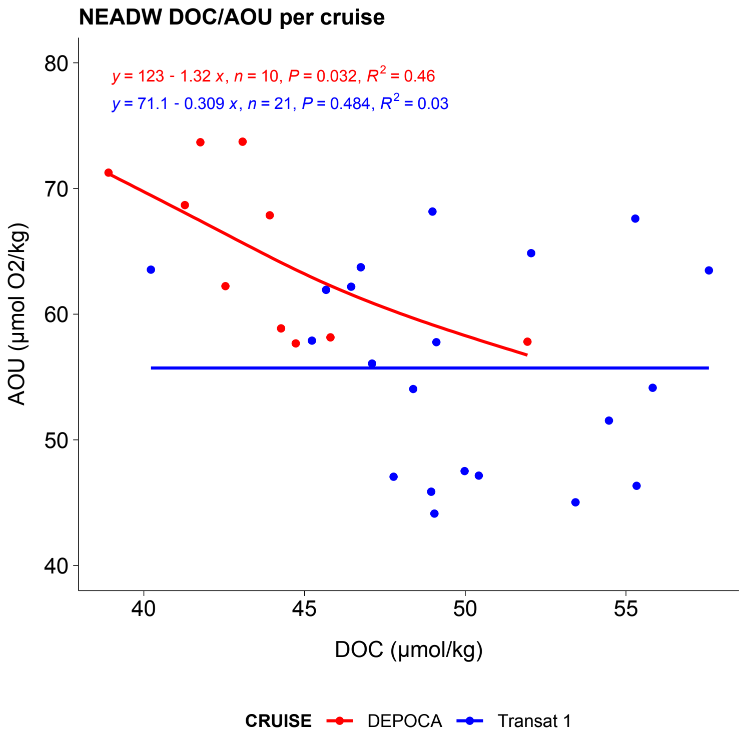


Figure 22: Relation between DOC concentration and apparent oxygen utilization (AOU)

While there was an inverse correlation between DOC concentration and AOU in 2023 (DEPOCA), there was no such relation detected in Transat 1 (Fig. 22).

DOC and inorganic nutrient ratios of the deep-water masses

The N:P ratios were generally slightly higher, albeit not significantly, in the year 2023 than in 2002 in all the deep-water masses (Table 2).

Table 2: Overview of the nutrient concentrations per area and water mass

Watermass / Cruise	NH4 (µmol kg-1) Average	SD	NO2 (µmol kg-1) Average	SD	NO3 (µmol kg-1) Average	SD	PO4 (µmol kg-1) Average	SD	N:P Ratio	DOC (µmol kg-1) Average	SD
north of CGFZ											
ISOW											
DEPOCA	0.05	± 0.01	0.01	± 0.00	16.75	± 0.50	1.10	± 0.04	15.2	47.39	± 1.49
Transat 1	0.12	± 0.05	0.01	± 0.00	15.99	± 0.65	1.08	± 0.04	15.0	46.52	± 16.74
LSW											
DEPOCA	0.05	± 0.02	0.00	± 0.00	17.10	± 0.46	1.11	± 0.03	15.5	48.01	± 1.39
Transat 1	0.10	± 0.05	0.01	± 0.00	17.26	± 0.26	1.14	± 0.01	15.2	45.30	± 19.69
around CGFZ											
LDW											
DEPOCA	0.04	± 0.01	0.00	± 0.00	16.90	± 0.31	1.11	± 0.03	15.2	45.50	± 0.85
Transat 1	0.10	± 0.04	0.01	± 0.00	18.01	± 1.54	1.21	± 0.11	15.0	48.61	± 3.19
LSW											
DEPOCA	0.03	+++	0.00	+++	16.87	+++	1.10	+++	15.4	44.26	+++
Transat 1	0.10	± 0.03	0.01	± 0.01	17.18	± 0.22	1.14	± 0.01	15.2	51.76	± 4.28
NEADW											
DEPOCA	0.04	± 0.00	0.00	± 0.00	16.71	± 0.20	1.09	± 0.01	15.3	47.34	± 4.06
Transat 1	0.10	± 0.04	0.01	± 0.00	16.74	± 0.24	1.12	± 0.02	15.1	50.84	± 2.60
south of CGFZ											
LDW											
DEPOCA	0.05	+++	0.00	+++	18.91	+++	1.25	+++	15.2	41.78	+++
Transat 1	0.10	± 0.03	0.01	± 0.01	21.41	± 0.83	1.44	± 0.06	14.9	38.39	± 22.80
LSW											
DEPOCA	0.05	± 0.01	0.00	± 0.00	17.72	± 0.28	1.13	± 0.01	15.8	63.26	± 39.75
Transat 1	0.09	± 0.03	0.01	± 0.01	17.41	± 0.20	1.15	± 0.02	15.3	52.49	± 4.70
NEADW											
DEPOCA	0.05	± 0.01	0.00	± 0.00	18.21	± 0.80	1.19	± 0.06	15.4	42.31	± 1.92
Transat 1	0.09	± 0.02	0.01	± 0.01	18.38	± 0.71	1.22	± 0.05	15.1	46.44	± 13.22

Prokaryotic abundance and biomass

Prokaryotic abundance was generally lower in the year 2023 than in 2002 (Fig. 23). The abundance of prokaryotes decreased significantly (n=32, p=.009, r^2=.1813) over the entire latitudinal transect in both years but more pronouncedly in the year 2002 (Fig. 23).The split into the areas indicated a lower decrease in prokaryotic abundance between 2002 and 2023 south of the CGFZ representing the older water masses than in the younger water masses north of and around the CGFZ (Fig. 23a).

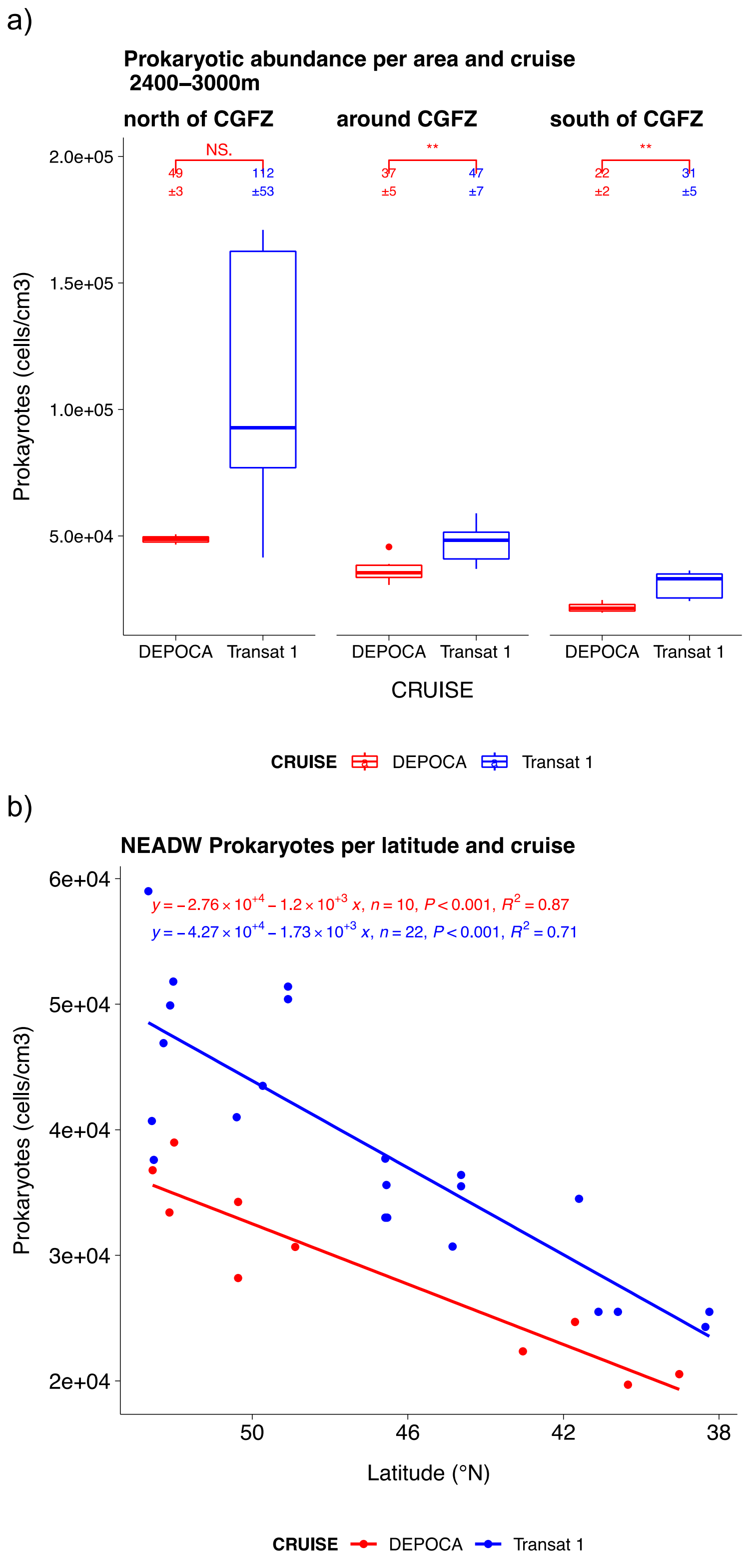


Figure 23: Prokaryotic abundance per area, the significance levels are given: ** indicates P<0.01, NS = not significant (a), abundance over the whole transect (b)

Prokaryotic biomass decreased significantly with depth (Fig. 24, n=270, p<.002, r^2=.868)

a) b)

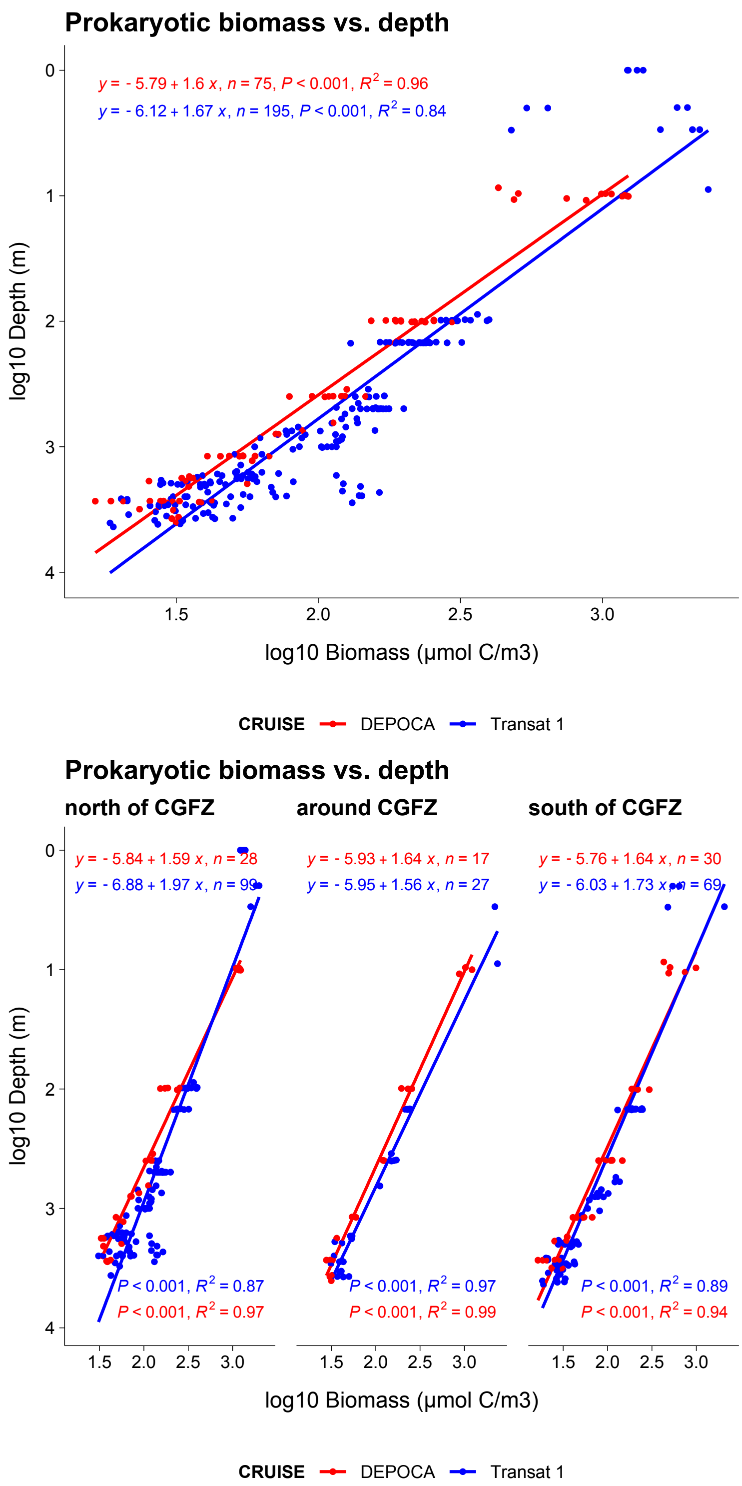
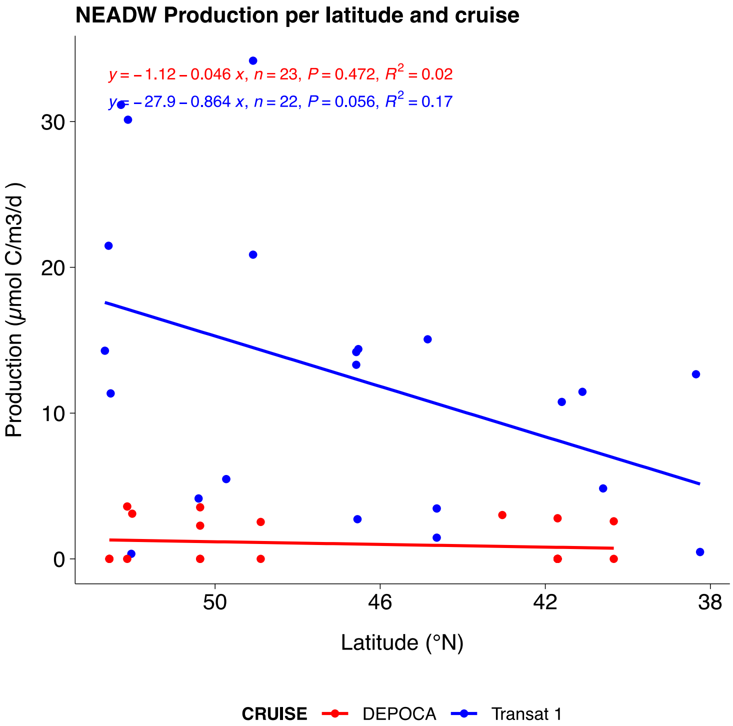


Figure 24: Decrease in biomass with water column depth (a), split into areas (b).

Prokaryotic heterotrophic production

Prokaryotic heterotrophic production in the NEADW was substantially lower in 2023 than in 2002 (Fig. 25a) resulting in a higher turnover time (abundance/production) in 2023 than in 2002 (Fig. 25b).

a)



b)

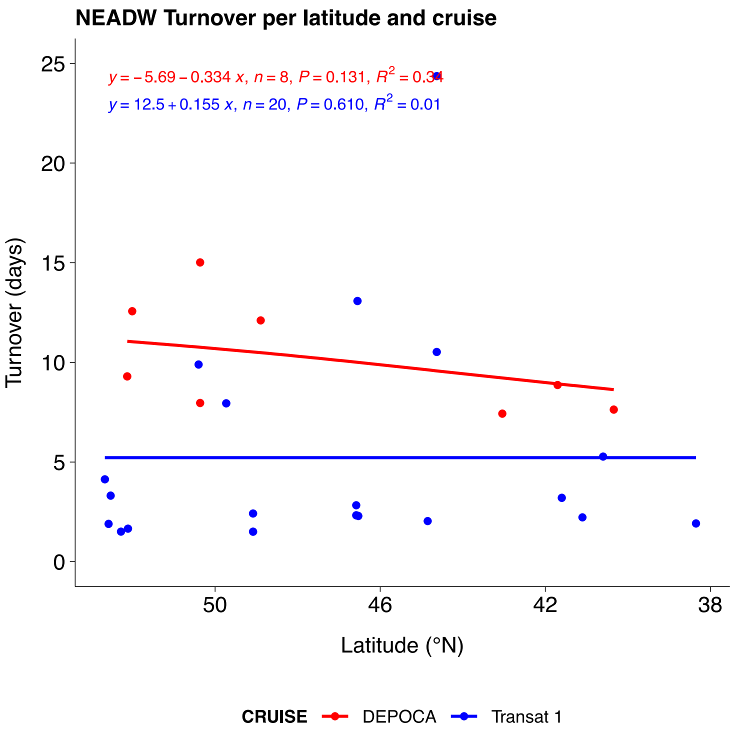
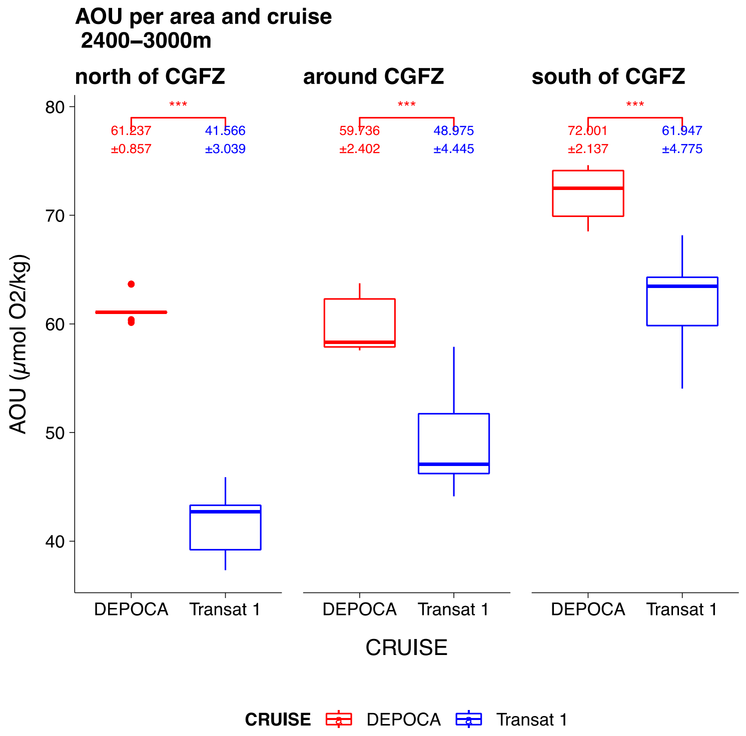


Figure 25: Prokaryotic heterotrophic production in the NEADW (a) and turnover time in days (b)

Respiration

In contrast to heterotrophic prokaryotic production, the apparent oxidation utilization (AOU) in the NEADW was higher in 2023 than in 2002 increasing with decreasing latitude (Fig. 26).

a)



b)

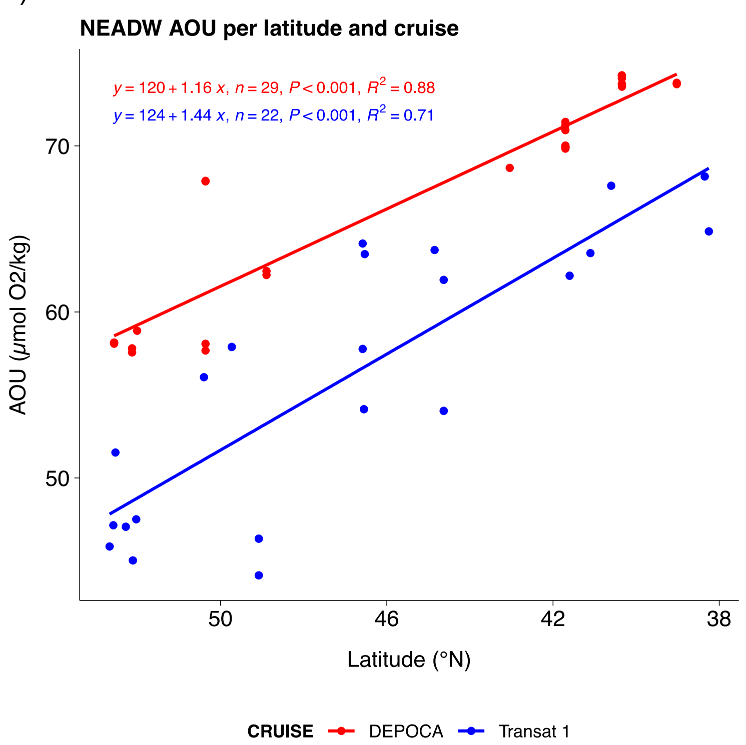


Figure 26: Apparent oxygen utilization (AOU) per area and cruise, the significance levels are given: *** indicates P<0.001 (a), NEADW across the transect (b).

Similar to the AOU trends obtained in the years 2002 and 2023, the deep Argo floats showed a similar increasing trend in AOU in the water masses between 2500 and 2800 m for the years 2015 to 2024 (Fig. 27).

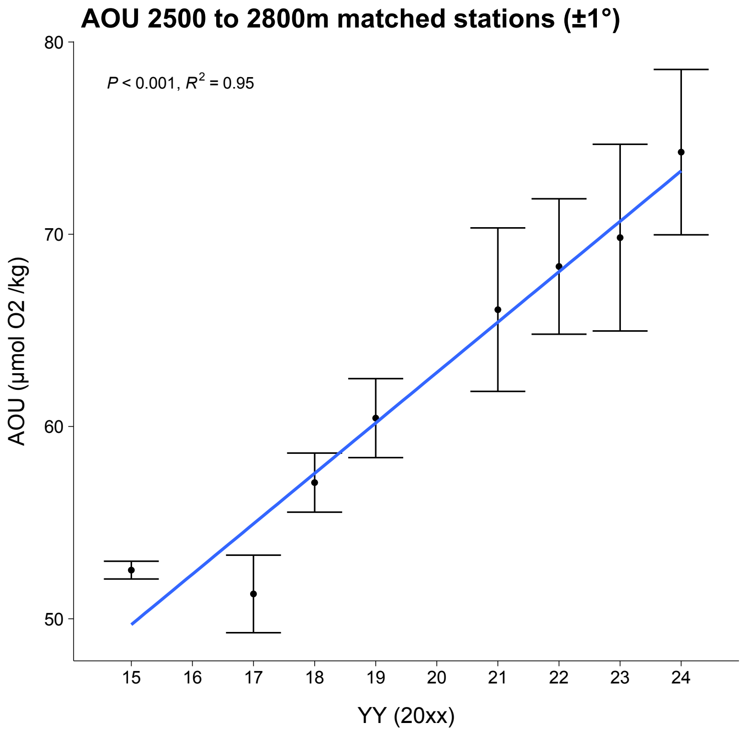


Figure 27: Deep-Argo AOU data for the NEADW along the transect between the years 2015 to 2024.

AOU and NO_3 increased with depth and from north to south along the sampled transect in the NEADW core water (Table 3).

Table 3: Nitrate and AOU per depth range in increments of 500m

Depth Range	DEPOCA				Transat 1			
	NO3		AOU		NO3		AOU	
	µmol/kg	SD	µmol O2/kg	SD	µmol/kg	SD	µmol O2/kg	SD
<500	9.50	± 6.04	25.34	± 25.82	11.56	± 5.56	21.59	± 24.46
500-1000m	17.97	± 0.36	68.07	± 14.05	18.66	± 1.00	76.76	± 16.53
1000-1500m	17.47	± 0.45	59.14	± 15.92	17.91	± 0.44	57.80	± 19.50
1500-2000m	17.23	± 0.62	54.01	± 3.20	17.11	± 0.59	37.30	± 4.80
2000-2500m	16.31	+++	54.58	± 0.11	16.30	± 0.65	41.15	± 3.48
2500-3000m	17.54	± 0.97	66.20	± 6.38	17.79	± 1.03	55.10	± 8.66
<3000m	17.52	± 0.93	63.42	± 4.98	19.79	± 2.11	70.24	± 15.52

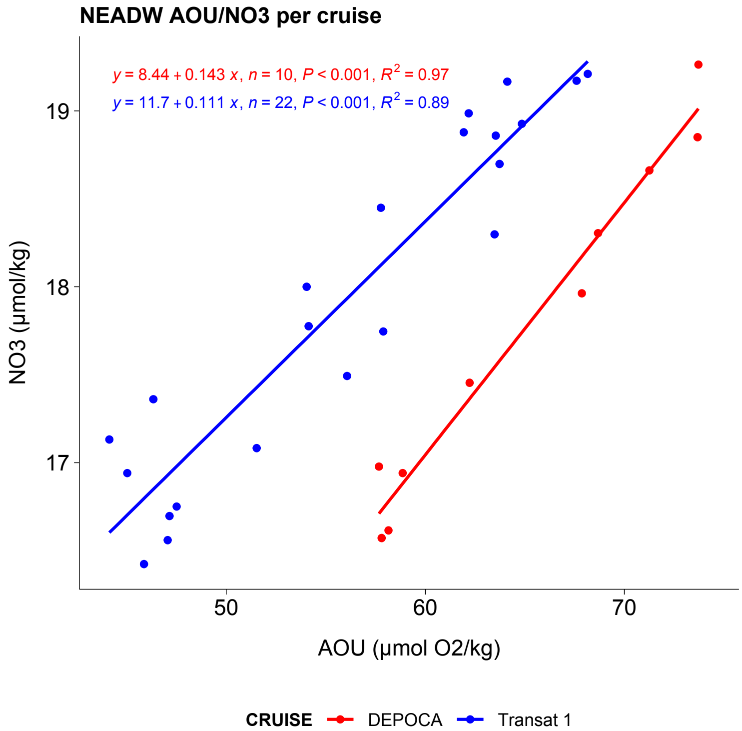


Figure 28: Relation between AOU and nitrate concentrations.

AOU and nitrate concentrations were tightly correlated in the NEADW in both years (n=32, p=0.001, r^2=.607) with similar nitrate concentrations but higher AOU values in 2023 (Fig. 28).

Summary

Table 4: Overview of biotic parameters per area and water mass. PHP-prokaryotic heterotrophic production.

Watermass	AOU (µmol O2 kg-1)		Prokaryotic abundance (N x 10e3)/cm e3)		PHP (nmol/m3/d)	
Cruise	Average	SD	Average	SD	Average	SD
north of CGFZ						
ISOW						
DEPOCA	55.81	± 6.23	54	± 11.75	1.66	± 0.58
Transat 1	41.00	± 4.68	106	± 50.21	8.71	± 9.61
LSW						
DEPOCA	49.76	± 5.30	54	± 18.96	1.71	± 1.48
Transat 1	34.14	± 2.25	66	± 13.22	3.46	± 1.98
around CGFZ						
LDW						
DEPOCA	60.62	± 1.51	38	± 1.00	1.42	± 0.61
Transat 1	57.28	± 11.70	51	± 5.47	5.03	± 4.31
LSW						
DEPOCA	50.77	± 0.03	44	+++	1.16	+++
Transat 1	36.83	± 3.13	58	± 9.33	4.88	± 2.40
NEADW						
DEPOCA	58.10	± 0.44	36	± 3.06	1.08	± 0.11
Transat 1	47.36	± 2.24	48	± 7.63	5.85	± 3.82
south of CGFZ						
LDW						
DEPOCA	74.14	+++	37	+++	1.18	+++
Transat 1	82.09	± 6.57	31	± 6.48	3.06	± 2.18
LSW						
DEPOCA	55.19	± 2.47	45	± 21.04	1.27	± 0.80
Transat 1	41.52	± 4.43	43	± 8.05	3.15	± 2.43
NEADW						
DEPOCA	69.53	± 4.97	26	± 5.34	0.90	± 0.14
Transat 1	59.37	± 7.02	35	± 8.15	3.42	± 2.79

AOU increased in all water masses, while the abundance of prokaryotes and prokaryotic heterotrophic production decreased in the water masses analyzed between 2002 and 2023.

Discussion

Physical characteristics of the North Atlantic deep waters

There is a decrease in salinity in the North Atlantic described previously (Stendardo et al., 2015). While Stendardo et al. (2015) focused on the mesopelagic layers, this decrease in salinity was also seen in the NEADW for the last two decades (Fig. 4 and 5). Also, the deep Argo data showed a clear decreasing trend in salinity over recent years (Fig. 6). As stated in the IPCC report 2021 (Intergovernmental Panel On Climate Change (Ipcc), 2023) an intensification of the hydrological cycle as a consequence of global warming is predicted. The changes propagating into the ocean’s interior are caused by freshwater input due to melting ice in the Arctic region as well as increased rainfall in the northern latitudes (Wu et al., 2005). The freshening is also detectable on the south side of the Atlantic. While in a comparison of the fifties to the sixties of the last century with the eighties to the nineties, there was practically no increase in temperature in the NEADW detectable but a clear freshening in salinity per year of 0.03 (Curry et al., 2003). While Curry et al. (2003) attributed this to the freshening of the LSW, the comparison over two decades shows a strong freshening north of the CGFZ in the ISOW (Fig. 5a). The freshening of the NEADW around the CGFZ and south of it is presumably attributable to a change in mixing of the water masses contributing to the NEADW.

The effect of the NAO index on the North Atlantic deep waters, especially via the LSW is described by Sarafanov (2009). Regarding the research cruises analyzed here, there were similar NAO conditions in the relevant winter season prior to the cruises (Fig. 7). Changes in the NAO have an impact on the AMOC and subsequently on the surface temperature and the stratification of the upper water masses (Kim et al., 2023), however, the NAO index was similar between the two years (Fig. 7). Thus, changes in temperature and salinity in the NEADW are not reflected by the NAO index.

In the NEADW, a clear temporal development towards decreasing oxygen concentrations and increased temperatures in the NEADW between 2002 and 2023 was observed. Even the Medea 2 cruise data of 2012 which was not part of this study was more in the range of the Transat data of 2002 compared to the 2023 data of DEPOCA (Fig. 29).

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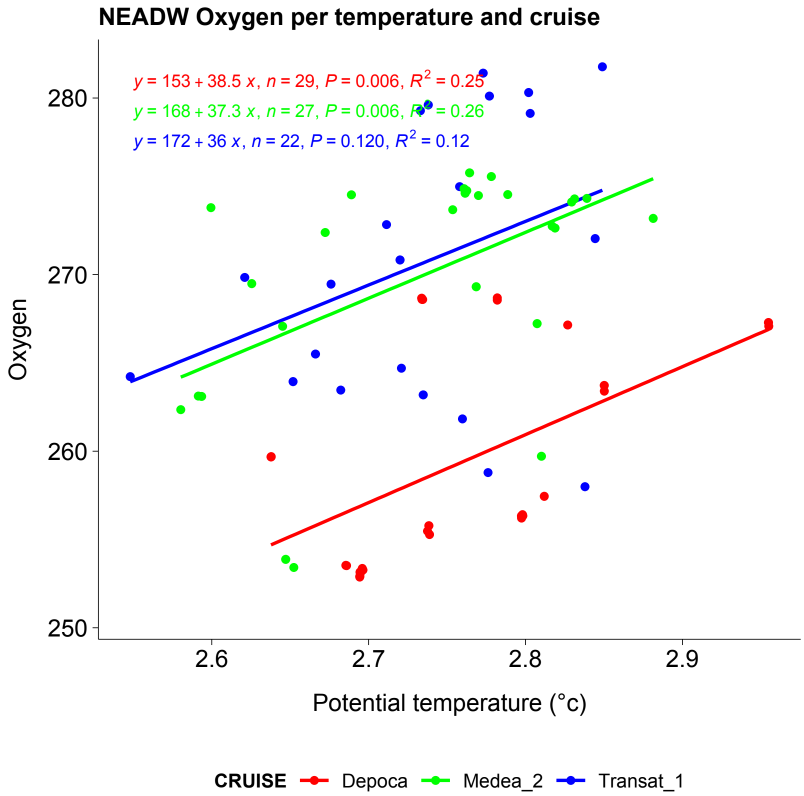


Figure 29: Relationship between potential temperature and oxygen concentrations in the NEADW in the years 2002 (Transat 1), 2012 (Medea 2) and 2023 (DEPOCA)

Despite the temperature increase not being significant, there are many changes in the NEADW over the past two decades.

Especially in the North Atlantic, the oxygenation level of the deep ocean became a focus of research (Stendardo et al., 2015). The vast majority of the variations of O_2 were attributed to the mixing of the water masses forming the NEADW (Reinthaler et al., 2013). Also, Racapé et al. (2019) analyzed the oxygen content with deep-Argo floats in this area. The negative impact of the freshwater input on the oxygenation was discussed by Jenkins (1999). Cassar et al. (2021) showed the various impacts on the O_2 concentration where sea ice melting and warming lead to decreases in oxygen concentrations.

An analysis of oxygen in the Gulf of St. Lawrence over more than 70 years showed a decrease of oxygen content of 50% at 250 m depth, mainly attributed to circulation changes (Levin, 2018). The negative trend on O_2 concentrations is increasing in recent years compared to previous periods and especially detected in the upper and intermediate waters of the North Atlantic (Levin, 2018).

The warming of the upper layers reduces the solubility of oxygen the seawater, following Le Chatelier’s principle (Levin, 2018). The freshening leads to an increased stratification and subsequently to a reduced mixing and vertical flux of nutrients (Keeling et al., 2010).

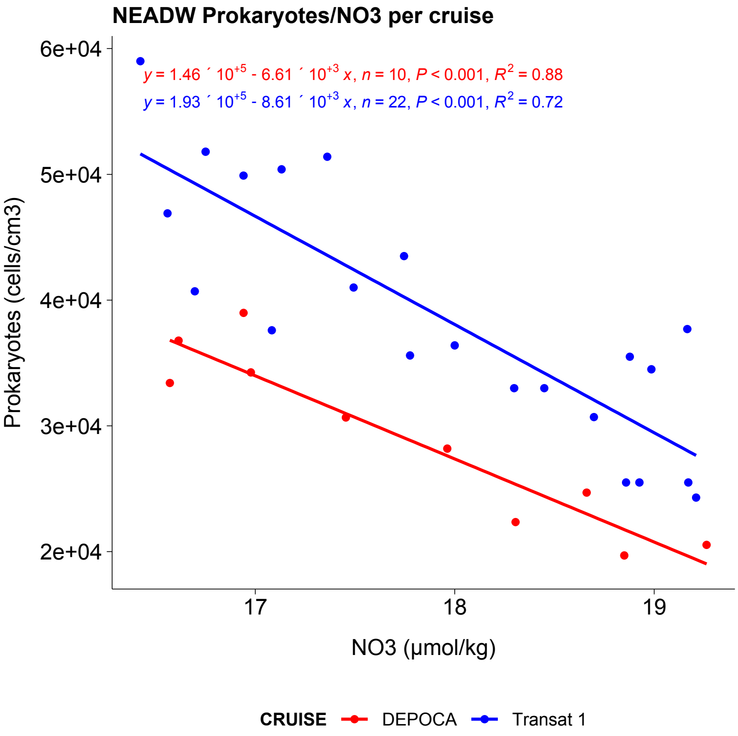
The stratification leads also to a reduced uptake of heat in the deep ocean (Barragán-Montilla et al., 2023) and subsequently to a less significant increase in temperature in deeper waters as compared to the upper layers. On one hand, the reduced downward supply of nutrients, would have a positive impact on the oxygen content of the deep ocean due to the limitation in abundance and respiration. On the other hand, the stratification limits the oxygenation of the dark ocean as shown by the lower O_2 concentrations (Keeling et al., 2010). The increase in ice melting in the Labrador Sea is also considered to be one source of the weakening of the Atlantic meridional circulation as shown in simulations (Madan et al., 2024). So, even without a significant increase in temperature in the interior of the ocean, the global warming is also impacting already the interior of the ocean and its biota.

Nutrients

The deep ocean shows a different picture regarding nutrients compared to the euphotic zone. While ammonium is depleted, oxidized forms of inorganic nutrients are readily available in the deep ocean (Nagata et al., 2010). This is also shown in Table 3. However, the timespan of 21 years shows a reduction of both oxygen and the oxygenated nutrients, coinciding with an increase in the AOU (Fig. 22).

For the oligotrophic North Atlantic it has been suggested that the limitation of N and P availability is responsible for the low prokaryotic heterotrophic productivity since the addition of labile DOC did not stimulate growth (Mills et al., 2008). The data of the two cruises show a clear inverse relationship between prokaryotic abundance and nitrate and phosphorus in the NEADW with generally lower prokaryotic abundance and nitrate and phosphate concentrations in 2023 than in 2002 (Fig. 30).

a)



b)

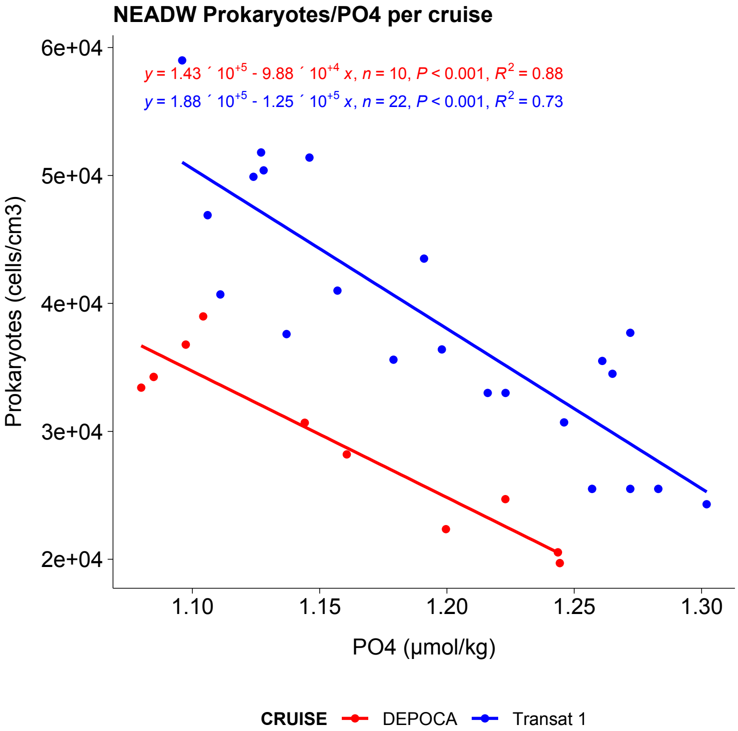


Figure 30: Prokaryotic abundance in the NEADW related to NO3 (a) and phosphate (b) concentrations.

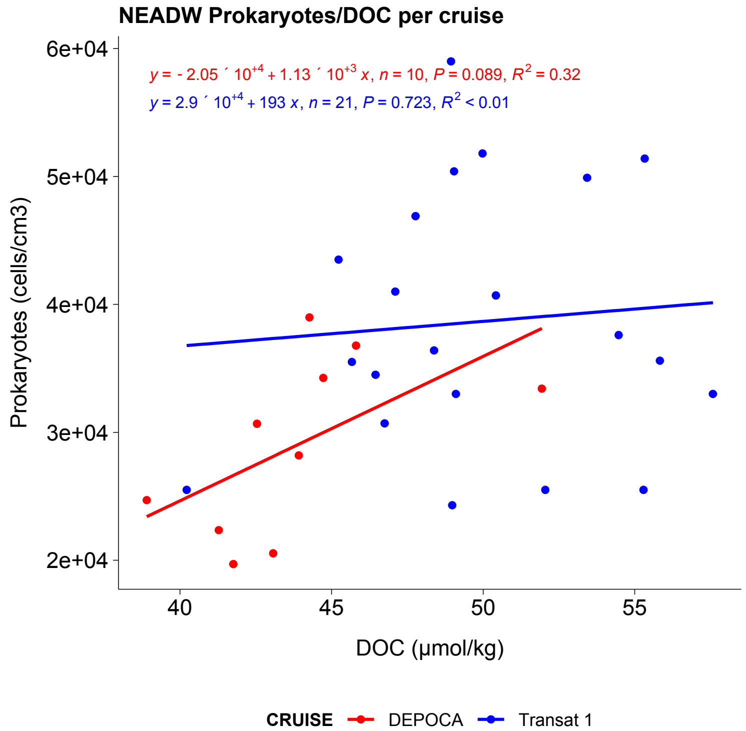


Figure 31: Prokaryotic abundance in the NEADW related to DOC concentrations.

Frank et al. (2016) detected a positive correlation of total organic carbon (TOC) with latitude. This could be demonstrated also for the DEPOCA data, while the Transat 1 data did not show any significant relation between DOC and latitude (Fig. 31).The latitudinal gradient of DOC as shown in Fig. 21 leads to the assumption that the vertical flux is mainly north of the 50°N associated with the younger water masses there and with a higher labile share than further south with a higher portion of recalcitrant DOC (Carlson et al., 2010). The comparison of the two cruises shows higher DOC concentrations in the ISOW and LSW north of the CFGZ than further south. Carlson et al. (2010) suggest that water masses with northward direction (LDW) could contribute to the low DOC content. LDW has a lower DOC content than the NEADW especially south of the CGFZ (Table 2). The vertical flux from the surface to the deep ocean is mainly occurring in the high latitudes due to downwelling and higher sinking rates of particles due to the larger phytoplankton cells than further south (Hansell, 2002). A change in the AMOC as predicted by many scientists (Van Westen et al., 2024) would dramatically change the spatial distribution of the vertical flux.

Biotic parameters decreased in the NEADW from 2002 to 2023

The decrease in prokaryotic abundance between 2002 and 2023(Fig. 32) coincides with the reduction in oxygen (Fig.13). Oxygen is the biggest driver of changes in abundance with a *p<.001 and an* r^2 of 0.853. However, the oxygen concentrations are sufficiently high to allow for aerobic respirations. Hence, the decrease in prokaryotic abundance cannot be caused by the declining O_2 concentrations in the NEADW.

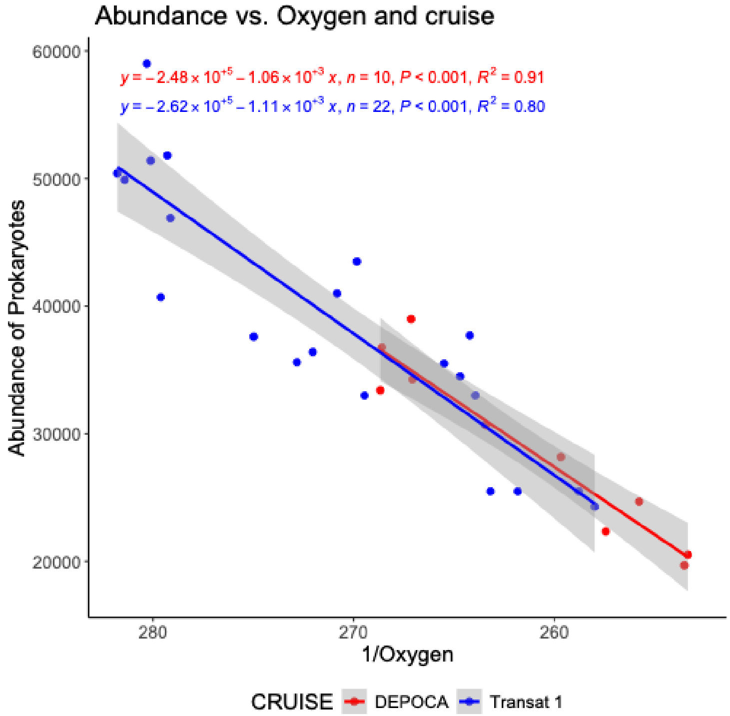


Figure 32: Ratio between prokaryotic abundance and oxygen in the NEADW

The latitudinal gradient in prokaryotic abundance as shown in Fig. 23 is also described by Reinthaler et al. (2013) for the northern part of the Atlantic.

The conclusion that a warming deep ocean would increase the production as mentioned by Lønborg et al. (2016) cannot be assumed as reason for the change in abundance. As shown in Fig. 33, the abundance in 2023 is consistently below the levels of those in 2002 even at the same temperatures. Also, the conclusion that deep sea taxa were more sensitive to temperature changes in a long-term stable environment (Yasuhara & Danovaro, 2016) does not reflect the changes in abundance described in this thesis.

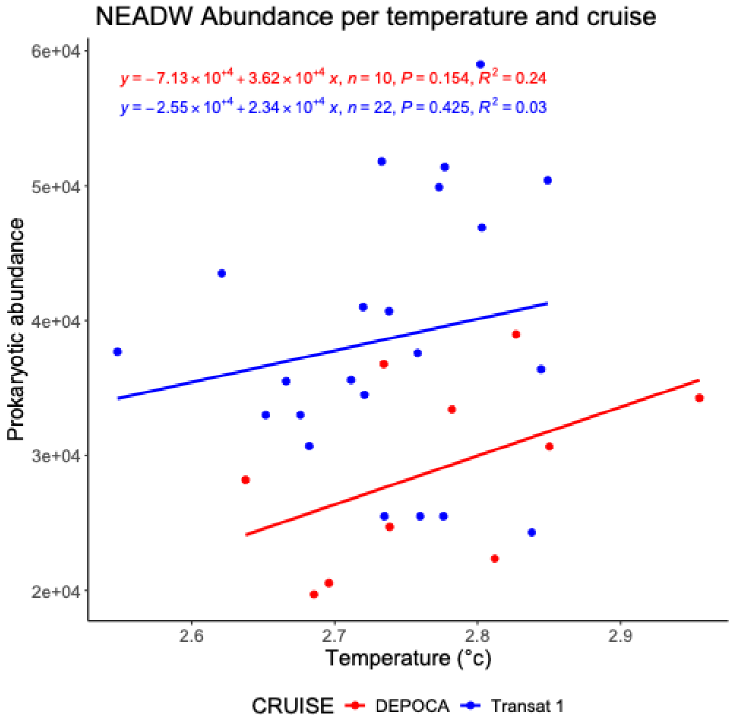


Figure 33 Relation between temperature and abundance in the NEADW

The decreasing production rates in the NEADW from north to south point to a decreasing bioavailability of organic carbon (Reinthaler et al., 2010). As the NEADW is formed north of the CGFZ, it is assumed that the easily available labile and semi-labile forms of organic carbon are mainly consumed there, while the more southern parts have a higher share of refractory carbon. The microorganisms themselves produce recalcitrant dissolved organic matter (RDOM) resulting again in biologically refractory carbonas proposed by the microbial carbon pump by Jiao et al.(2010).

Conclusion

The comparison of the physico-chemical and microbiological parameters in the deep North Atlantic over two decades showed impacts of global warming on various parameters. A temperature increase in all the water masses analyzed was evident and higher in the Iceland-Scotland-Overflow Water in the north than further south in the North Atlantic. However, the temperature increase in the NEADW is not that strong yet.

A significant change is the ongoing freshening of the water masses which is especially strong in the area north of the CGFZ, corresponding to the younger water masses. Coinciding with this, the oxygen concentration of the deep ocean is significantly declining over the whole stretch of the transect. This is also clearly visible in the deep-Argo data for this area since their deployment in 2015.

Both, the oxygen and the inorganic nutrients decreased as well as the microbial biomass in the deep ocean between the years 2002 and 2023.

Thus, the research question “Is there an impact of the global warming in terms of physico-chemical and microbiological parameters detectable in the North Atlantic Deep water and adjacent water masses?” can be answered. Global warming did not only arrive at the starting point of the conveyor belt of the deep ocean but also changes the various of physico-chemical and microbiological parameters particularly in the northern region of the North Atlantic and will propagate as the NADW is transported southwards.

Tables and Figures

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