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# Hydrographic Conditions Around Offshore Banks

**Philip Axe & Helma Lindow**

**Rapport**

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# Contents

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# 1 Summary

This report details the results of an investigation into hydrographic and hydrochemical conditions over ten offshore banks around the coast of south Sweden. Four of these banks are situated in the Kattegat. The remainder lie in the southern and western Baltic Proper. The investigation included field sampling, where each bank was visited on one occasion, and the temperature and salinity structure mapped while the concentrations of nutrients were measured. These data were analysed, and results compared and complemented with predictions from operational numerical models (for currents and waves).

The banks are areas with strong horizontal gradients in temperature and salinity. They influence the large scale circulation, steering mean currents through the deeper water, resulting in the mean currents over the banks being weak. The influence of short term wind events are significant however, with intense, short-lived currents occurring over the banks.

Nutrient concentrations in the waters above the banks were very similar to those in the adjacent basins. Immediately over the bottom however, silicate concentrations were often higher than at similar depths away from the banks. Similarly, oxygen saturation immediately above the bottom was frequently lower than in mid-water at the same depth.

In the Kattegat, large areas are at risk from seasonal oxygen deficiency. The shallow nature of the banks however often means that they escape the worst impacts.

# 2 Introduction

In 2003, the Swedish government requested the Swedish Environmental Protection Agency (*Naturvårdsverket*) to draw up an inventory of the marine environment in areas likely to be of interest for offshore wind farm development, and to identify areas of particular environmental value. The project was intended to give an overview of the extent of various habitats around banks, and their particular environmental 'value'. This overview will be used for guidance by the Environmental Protection Agency and county administrations when considering planning applications for developments affecting the banks.

The following areas, within the 30 metre depth contour, were considered to be the most suitable for investigation:

| | |
|---|---|
| Skagerrak: | Persgrund |
| Kattegat: | Fladen, Lilla Middelgrund, Stora Middelgrund, Röde Bank |
| Baltic Proper: | Kriegers Flak, Södra Midsjöbanken, Norra Midsjöbanken, Hoburgs Bank, Knolls Grund, Ölands Södra Grund |
| Gulf of Bothnia: | Finngrundet, Storgrundet, Vänta Litets Grund, Väktaren, Rata Storgrund, Klockgrundet, Rödkallen |

The project involves geological surveys, using seismic, sidescan, grab and visual investigations carried out by the Swedish Geological Survey, as well as biological surveys using divers, remotely operated vehicles (ROV) and towed camera systems carried out by biologists from the three principle Swedish university marine research centres (Umeå, Stockholm and Gothenburg). To form a basis for interpreting the biological (and to a lesser extent, geological) data, SMHI and Umeå Marine Research Station were requested to make measurements of the hydrography across the banks - in particular to see if the banks had special stratification or circulation characteristics which could affect biological processes.

Results of SMHI's measurements are presented in Chapter 3. In addition, SMHI were asked to undertake a preliminary investigation of conditions over the Kattegat banks, using existing oxygen and hydrography data. These are presented in Chapter 4.

During progress meetings, it became clear that the wave climate over the banks was of interest, particularly in terms of oscillatory bottom currents due to waves. These can be sufficiently strong to remove finer sediment and poorly-adapted organisms. SMHI runs a second-generation wave model covering the entire Baltic with a spatial resolution of 11 km, with data output every three hours. The model is driven by wind data from SMHI's principal meteorological model. Modelled wave data, covering several years, have been analysed to show the frequency of occurrence of maximum current speeds velocities over various bottom depths.

Progress meetings also indicated an interest in circulation around the banks, and in particular how the banks affected currents, and whether this leads to the retention of larvae over the bank areas. Two approaches were taken to this problem. The first was based on the density profiles taken during this project, which were analysed to see if sea level gradients existed over the banks. The other was based on data from SMHI's three-dimensional ocean circulation model. This covers the Baltic and North Sea with a horizontal resolution of 12 nautical miles (nm). Within this model domain, two higher resolution versions are also run, covering the Baltic at 3 and 1 nm resolution respectively. This model provides profiles of temperature, salinity and current velocity (among other parameters) at every grid point. These data were analysed to show both extreme currents and any residual circulation around the banks.

# 3 Observations

SMHI was asked to make hydrographic (and hydrochemistry) observations at between five and nine stations across each of the following banks:

| | |
|---|---|
| Kattegat: | Fladen, Lilla Middelgrund, Stora Middelgrund, Röde Bank |
| Baltic Proper: | Kriegers Flak, Södra Midsjöbanken, Norra Midsjöbanken, Hoburgs Bank, Knolls Grund, Ölands Södra Grund |

Measurements were taken during SMHI's monitoring cruises between October 2003 and January 2004. Sampling locations are shown in Figure 1 and Figure 2, for the Kattegat and Baltic Proper respectively. Locations were selected from Sjöfartsverket charts and geological maps from Sveriges Geologiska Undersökning (Swedish Geological Survey). Some sample stations were in water deeper than 30 metres, for use as control points showing conditions adjacent to the banks, so the extent of any particular 'bank characteristics' could be better mapped. Two transects, roughly perpendicular to each other, were made over each bank, with the exception of Lilla Middelgrund and Röde Bank, in the Kattegat, where one transect across each bank was taken.

Data were quality controlled using thermometers and salinometer measurements from the water bottle samples, and have been binned into 0.5 dbar pressure (approximately equivalent to 0.5 metre depth) bins, after removal of spikes and profile reversals. In addition to hydrography, SMHI was also requested to take nutrient (ammonium, nitrate, nitrite, phosphate, total nitrogen and phosphorus, as well as silicate) and oxygen measurements from water bottle samples at 'standard' depths. The standard depths are those used in the HELCOM COMBINE programme[1]. Plankton, pH, alkalinity, humus and lignin were not measured. Measurements were made by SMHI's Oceanographic Laboratory, which is accredited according to ISO 17025:1999. Measurement ranges and precision are detailed in Table 1. Station positions were obtained from the (differential) GPS system on board U/F Argos. Horizontal positions and vertical datum were relative to the WGS 84 reference ellipsoid.

The hydrographic and hydrochemistry data obtained at each bank is presented below:

[1] Standard Helcom depths are were 0, 5, 10, 15, 20, (25), 30 metres, & 1 metre above the bottom. Samples were taken at 25 metres in the Kattegat only. http://www.helcom.fi/helcom/groupstaskforce/helcommonas.html#combine

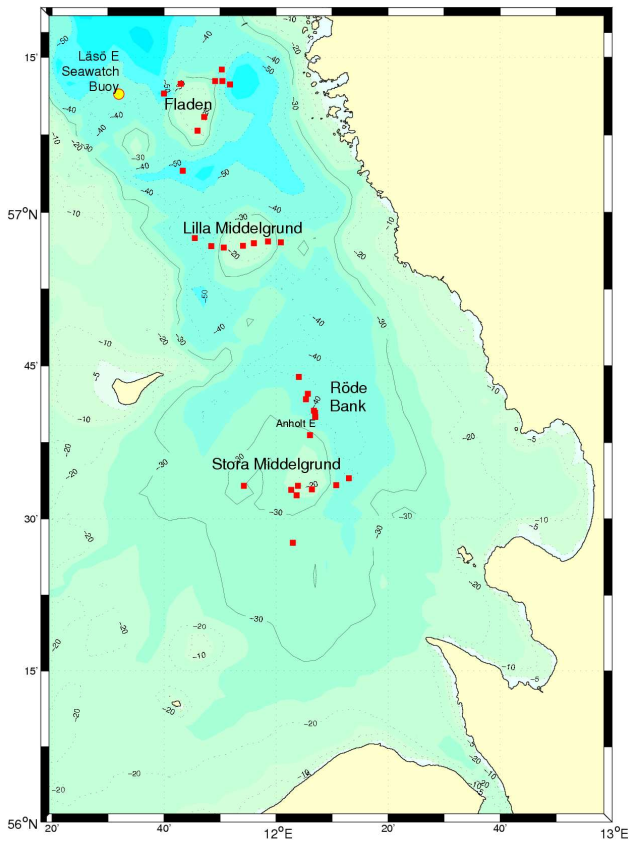


***Figure 1** Hydrographic stations taken across the Kattegat Banks, October – December 2003*

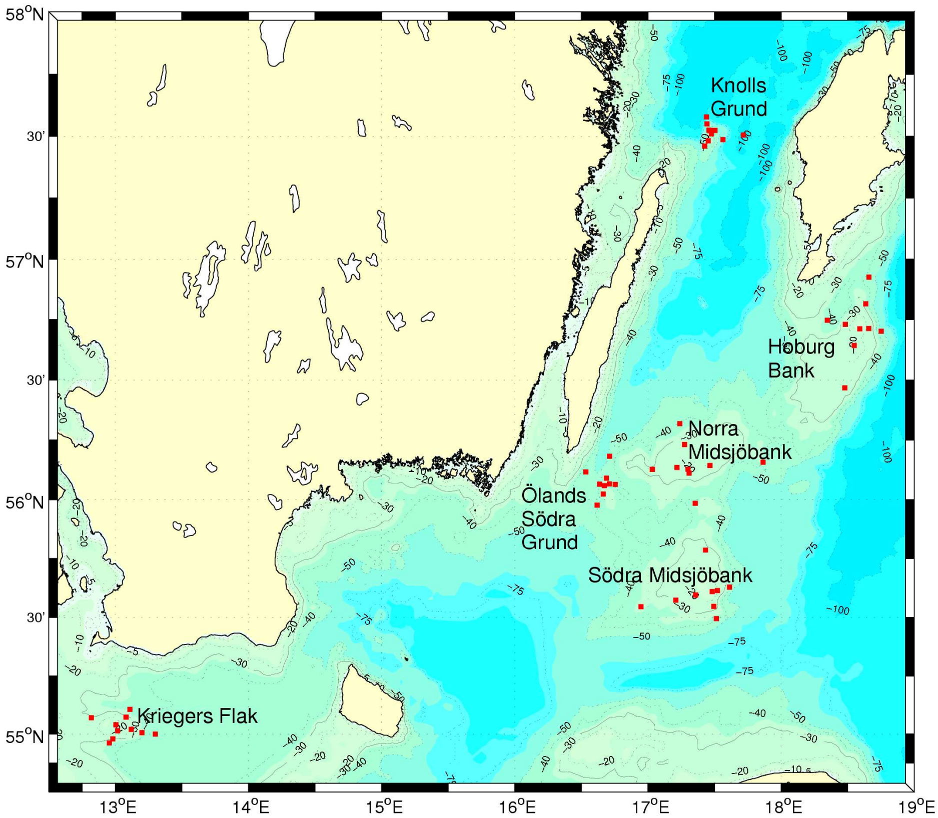


***Figure 2** Sampling stations over banks in the Baltic Proper: October 2003 – December 2004*

| Parameter | Unit | Precision | Range | Method |
|---|---|---|---|---|
| Temperature | °C | ±0.05°C | -2.5-38 | Electronic Thermometer |
| | °C | ±0.05°C | | CTD |
| Salinity | (PSU) | ±0.010 PSU | 2-40 | Laboratory salinometer (conductivity) |
| | (PSU) | ±0.05 PSU | | CTD |
| Oxygen | ml/l | ±1.0% | 0.02-15 | Iodom. titration |
| Oxygen saturation | % | ±1.2% | | |
| Hydrogen sulphide | µmol/l | ±4% | 0.5-300 | Man. Spectrometry |
| Ammonium | µmol/l | ±28% | 0.05-0.30 | Man. Spectrometry |
| | µmol/l | ±10% | 0.30-30 | Man. Spectrometry |
| Nitrite | µmol/l | ±17% | 0.02-0.2 | Aut. Spectrometry |
| | µmol/l | ±5% | 0.22-3.0 | Aut. Spectrometry |
| Nitrate | µmol/l | ±11% | 0.10-1.5 | Aut. Spectrometry |
| | µmol/l | ±3% | 1.5-25 | Aut. Spectrometry |
| Ortho-Phosphate | µmol/l | ±24% | 0.02-0.20 | Aut. Spectrometry |
| | µmol/l | ±3% | 0.20-4 | Aut. Spectrometry |
| Silicate | µmol/l | ±10% | 0.2-5.0 | Aut. Spectrometry |
| | µmol/l | ±5% | 5.0-100 | Aut. Spectrometry |
| Nitrogen, total | µmol/l | ±14% | 5.0-45.0 | Persulphate oxidation |
| Phosphorus, total | µmol/l | ±23 | 0.1-1.0 | Persulphate oxidation |
| | µmol/l | ±8% | 1.0-4.0 | Persulphate oxidation |

*Table 1* *Physical & chemical parameters analysed at SMHI:s accredited laboratory. Precision is (calculated according to the requirements of ISO/IEC 17025:1999) using the so-called expanded measurement uncertainty. The reported uncertainty is calculated with a spreading factor of 2, which gives a confidence interval of about 95%. The laboratory accreditation also covers measurements taken within the HELCOM COMBINE programme.*

## 3.1 Kattegat Banks

### Fladen Bank

Fladen was visited between 0219Z and 0835Z on 11th December 2003. During this time, atmospheric pressure was steady (1004 hPa, increasing to 1008 hPa during the last cast) and winds were fresh (8 – 10 $ms^{-1}$) from the south and south-southwest. CTD casts were taken at nine stations, forming a cross pattern centred over the northern, shallowest, end of the bank.

Physical properties from each profile were very similar both at the bottom (around 9.5°*C*; 34 *psu*) and at the surface (6°*C*; 22.5 *psu*). Between 8 m and 16 m depth, the two westernmost profiles were warmer and fresher than the remainder, while those from the north and east of the bank were both colder and more saline (Figure 15). Above 20 metres, profiles 808 and 809, from the southern side of the bank, lay between the extremes of the western two stations and the remainder .Mixed layer depth varied between 6 (profiles 815 and 816) and 11 metres (profile 812). The narrowest mixed layer occurred to the west of the bank in relatively deep water while the deeper occurred on the leeward side of the bank. This may be due to the bank focussing waves as they pass over, leading to higher waves and more mixing on the leeward side. This leeward profile also had the strongest stratification found over the bank, at the bottom of the mixed layer. Weakest stratification was found over the bank crest, at profile 0810.

Highest total nitrogen concentrations were found at the surface (around 16 *μM*[2]). Below 15*m*, levels were lower - around 12*μM*, before increasing below 50 *m*. Dissolved Inorganic Nitrogen (DIN) was composed mainly of nitrate, though both nitrite and ammonium were present, particularly deeper than 15 *m* from series 814 – 816, along the northwestern side of the bank. DIN accounted for between about 20 and 50% of the total nitrogen content. Phosphorus and silicate concentrations showed little variation with station or depth. Orthophosphate ($PO_4$-P, or Dissolved Inorganic Phosphorus) had lowest concentrations at the surface – around 0.3 *μM*, with concentrations increasing to 0.6*μM* at 60 metres. At the surface, DIP accounted for about 70% of the total phosphorus, while at the bottom, concentrations were almost equal, suggesting that all deep water phosphorus was DIP.

Oxygen levels were generally good, which is to be expected given the time of year of sampling. All samples were higher than 5 *ml/l*, with the exception of two. At 40 metres, along profile 808 (the southernmost sample), there was a minimum of 4.5 *ml/l*. Higher levels were observed both above and below. Minima also occurred in both silicate and nitrogen (DIN and total) concentrations from this sample, possibly indicating some biological activity at this depth, though no fluorescence signal was seen in the CTD data. The samples were not handled differently to any others, and the values obtained could not be due to the sampling bottle closing at the wrong depth.

### Lilla Middelgrund

Lilla Middelgrund was sampled between 2135Z on the 10th December and 0035Z on the 11th December 2003. Winds were increasing from fresh to strong (8 – 11 $ms^{-1}$) from the south – southsouthwest as the pressure dropped from 1010 to 1007 *hPa*. Profiles were taken from seven stations, extending along a west – east line across the bank.

Surface salinity (and density) varied across the bank, increasing from west to east. All profiles bar one (series 806) had a well defined surface mixed layer, extending to 8 – 10 metres depth. Thermocline and halocline were coincident in all profiles. Strong stratification (buoyancy frequency > 0.03 $s^{-2}$) was found at the bottom of the mixed layer over the shallowest part of the bank (series 805) at 8 metres depth, in 10 metres of water. Adjacent stations (series 804 and 806, in 12 and 25 metres water respectively) had considerably weaker maximum stratification.

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[2] The surface sample from the bank crest had a concentration of 23 μM. This was attributed to a contaminated sample

Total nitrogen levels were high at the surface (14 – 17 $\mu M$) though DIN levels were considerably lower – up to 5 $\mu M$ in the top 10 metres. The CTD fluorimeter indicated some phytoplankton activity in the surface mixed layer and pycnocline, despite the time of year. Peak fluorimeter values were also higher over the bank top (0.32 - 0.38$V$ from series 805, 804 and 803, compared with 0.24 – 0.29$V$ from the remaining series). The higher fluorimeter values came from the bottom of the mixed layer over the bank, whereas the lower values came from 5 metres or above (Figure 3). Total phosphorus levels were low (up to 0.8 $\mu M$). DIP levels in the surface were about 70% of the total phosphorus concentration, but below 10 metres DIP and total phosphorus had almost the same concentration. Stations over the bank top appeared to have slightly lower ratios of DIP:total phosphorus, possibly indicating more biological activity over the bank. There was otherwise very little variability with depth. Silicate showed no variation across the bank, though concentrations were lower (~6 $\mu M$) in the surface water (above 20 metres) than deeper, where concentrations were close to 10$\mu M$. Oxygen concentration was better than 7 *ml/l* at the surface, but had decreased to just over 6 *ml/l* at the bottom of the shallowest profile. Below 20 metres, levels were constant just over 5 *ml/l*.

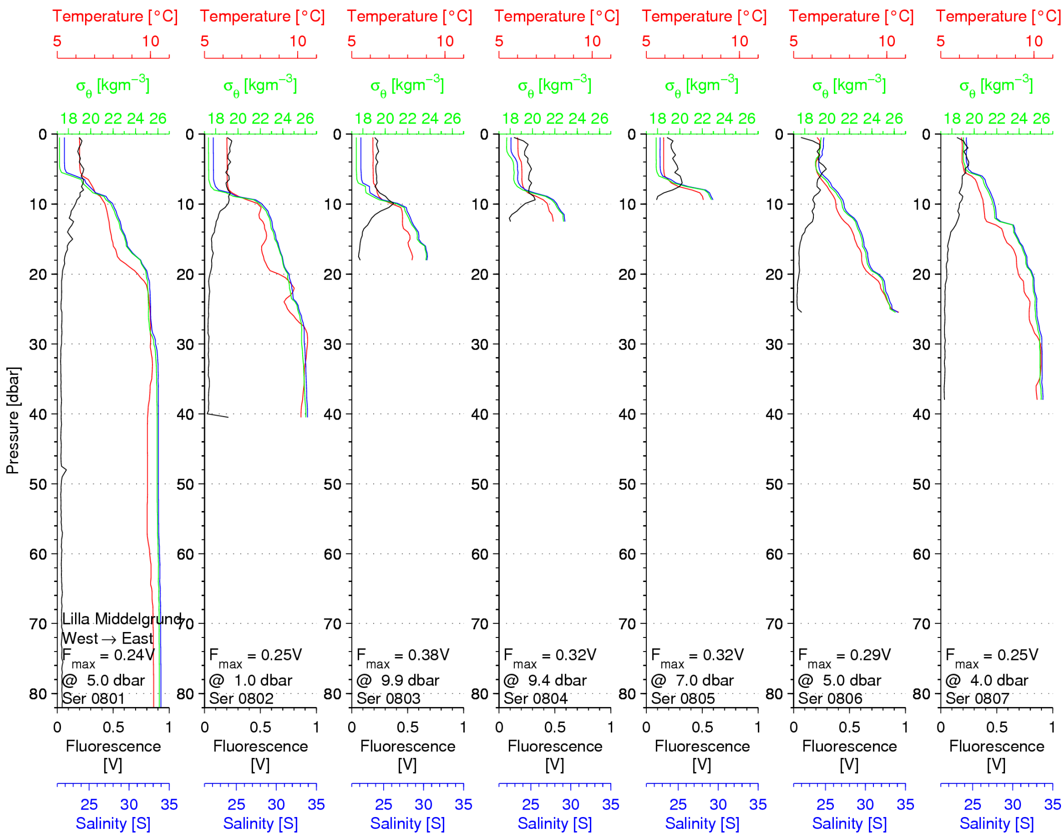


*Figure 3 Temperature, salinity and fluorimeter profiles across Lilla Middelgrund.*

## Röde Bank

Röde Bank was sampled between 0200Z and 0455Z on 24th October 2003. Winds were light to gentle (2 – 5 *m/s*), cyclonic then westerly. Atmospheric pressure was steady at 1016 *hPa*. It was not easy to locate the bank, as the depth over the charted crest position was 25 metres. Bottom depths at the sampling locations varied from 60 to 25 *m*.

Surface temperature was close to 8.1°*C*, though a strong gradient existed between series 656 and 657, with surface temperatures of 8.03 and 9.03°*C* respectively (Figure 30). Surface salinity varied between 15.8 *psu* at series 656, to 18.26 *psu* at 660. Again, a strong gradient (almost 2 *psu* over 400 metres) existed at the surface between series 656 (15.8 *psu*) and 657 (17.75 *psu*). Below the 17 $kgm^{-3}$ density surface, water properties were very similar from each profile. The depth of the 17 $kgm^{-3}$ surface deepened over the bank, from 7 metres in the south to 10 metres in the north. Maximum buoyancy frequency, a measure of stratification strength, varied between 0.018 and 0.027 $s^{-2}$. This is lower than was found at Fladen and Lilla Middelgrund, probably due to the sampling season. The upper 22 metres was stably stratified, with small steps in the profile indicating that the summer stratification had not yet been completely mixed away, whereas the other banks (sampled later) had a well defined surface layer. The buoyancy frequency maximum was located at between 20 and 22 metres at all profiles, except over the bank crest, where it was found at 4 metres, in 25 metres of water.

A further indication that summer conditions were not over was the DIN-concentration. This was close to zero in the upper 10 metres. Around 15 *m*, ammonium made up a significant proportion of what DIN existed. Meaningful amounts were only apparent from 20 metres. Surface DIP concentrations were also low, about a third of the total phosphorus concentration. From 20 metres, phosphorus concentrations increased, and the proportion of phosphorus present as DIP increased to around 90%. Silicate concentration was about 8 $\mu M$ in surface water across the bank. Each profile showed a concentration minimum between 5 – 15 metres. Oxygen saturation was close to 100% in the top 15 metres, with a couple of measurements at 5 metres showing some supersaturation – a sign of phytoplankton activity. By 40 metres depth, oxygen saturation had fallen to between 40 and 80%. Over the bank crest, saturation at the bottom was below 60%, despite the relatively shallow depth.

### Stora Middelgrund

Stora Middelgrund was visited between 1145Z and 1820Z on the 10th December 2003. Winds were fresh – strong (10 – 13 m/s) from the southeast at the beginning of sampling, before weakening to 7 m/s and veering to southerly. Atmospheric pressure decreased from 1017 to 1013 hPa during this time.

Surface temperatures were around 6.5°C during sampling, and most profiles had a surface salinity close to 22 psu. Series 800, 794 and 795, which lie to the east and north of the bank, had a surface salinity below 21 psu, to a depth of 6.5 *m* to the east of the bank, and almost 10 metres to the north. The surface mixed layer was very well defined, extending down 18 metres (in 31 metres of water) to the west of the bank, though only 10 – 12 metres over the bank top. East of the bank crest, the surface mixed layer did not extend below 6 metres, and the stratified region was broad, extending 10 metres below the surface layer. West of the bank, the pycnocline was only two metres wide, and found at 23 metres. The broad pycnocline east of the bank is reflected in the peak buoyancy frequency figures, which were 0.06 $s^{-2}$ to the west, compared with 0.02 $s^{-2}$ to the east. The transect from south to north had a narrow surface mixed layer – extending to 11 metres deep south of the bank (profiles 791 and 792) though only between 5 and 7 metres deep over the bank crest. The gridded temperature, salinity, density and buoyancy frequency along each transect are shown in Figure 38. Strong horizontal gradients over the bank crest are apparent in each panel. The buoyancy frequency panels show the weak stratification in the surface layer, and the pycnocline's depth change as it crosses the bank crest. Over the bank, stratification appears weaker than away from the bank (in particular profiles 797 – 799, in contrast to 791, 796 and 800).

Total nitrogen concentration varied between 15 - 22 $\mu M$ in the top 15 metres. South of the bank, from 0 – 20 metres, and from 0 – 10 metres north of the bank, DIN levels were constant, around 4 $\mu M$. Below these levels DIN concentration increased to about 6 $\mu M$, and the proportion of ammonium dropped from 0.5 – 0.8 $\mu M$, to below 0.1 $\mu M$. Phosphorus concentrations, both DIP and total, were below 1 µM. Above the pycnocline, DIP concentration was around 0.4µM, and made up about 60% of the total phosphorus concentration. Below the pycnocline, almost all phosphorus (0.8 µM) was present as DIP. Silicate concentration showed very little variation with depth or profile. Concentrations were about 9 µM. A local maximum occurred at 15 metres depth, along profiles 794, 795, 799 and 800, where concentrations reached 10 – 16 $\mu M$. Oxygen saturation (Figure 44) was 100% between the surface and 10 metres, and even down to 20 metres to the south of the bank (even close to the bank crest). Closer to the bottom, oxygen concentration reduced to between 60 and 80%.

## 3.2 Baltic Banks

### Kriegers Flak

Kriegers Flak was visited on the 23rd October, between 0725 and 1455Z. Ten profiles were taken, including one east of the bank at BY1 (a Baltic Monitoring station describing the central Arkona Basin). The stations form a cross over the shallowest part of the bank, from east to west and south to north. Weather during sampling was clear, with little cloud. Winds were gentle - moderate breezes (5 – 8 m/s) from the north and northeast. Atmospheric pressure was stable at 1018 hPa, decreasing to 1016 hPa for the last two profiles.

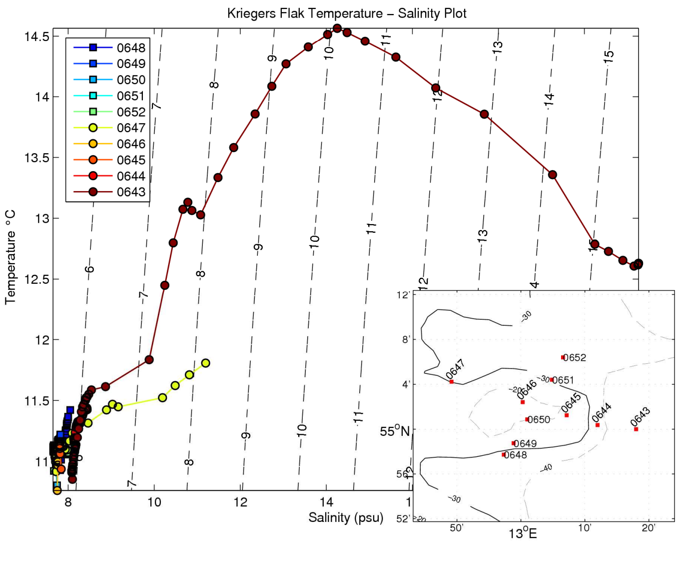


*Figure 4 TS-diagram across Kriegers Flak*

The temperature-salinity plot (*Figure 4* and *Figure 45*) is dominated by profile 643, taken at station BY1. This station shows the conditions in the centre of the Arkona basin, where there was a warm layer, which profile data showed to exist around 38 metres. Both the thermocline and pycnocline were found between 30 and 40 metres, and the bottom layer water appeared to be homogenous below 42 metres. The next longest profile was series 647, south of Falsterbo, and west of the bank. This station was very weakly stratified in the top 20 metres. The pycnocline proper started at about 25 metres and extended to the bottom.

Over the bank itself, the stratification was much weaker – peak buoyancy frequencies lay between $10^{-5}$ and $10^{-4}$ $s^{-2}$. North of the bank, and over the crest salinity was close to 7.7 *psu* in the upper 20 metres. To the south and east it was higher (7.9 – 8.1 *psu*), and lower to the north.

The weak stratification was reflected in the nutrient values. Total nitrogen concentration varied between 17 and 19 $\mu M$ along the west – east transect, with very little variability with depth. The only significant DIN concentrations were at 40 metres, from profile BY1. Similarly, total phosphorus, DIP and silicate had very little variation across the bank or with depth. Total phosphorus concentrations were around 0.5 $\mu M$, with DIP levels about half that. Silicate concentration was around 8 $\mu M$. Only at 40 metres at BY1 were phosphorus concentrations above 1 $\mu M$ found. At this depth, all the phosphorus was present as DIP. Silicate concentration was also higher, around 23 $\mu M$. Oxygen saturation was close to 100% at all stations and depths, except for 40 metres and just over the bottom at BY1. At 40 metres, saturation was below 60%, though increased to almost 80% at the bottom.

### Ölands Södra Grund

Ölands Södra Grund was visited on the 19th January 2004, between 0955 and 1650Z. Nine profiles were taken in a cross pattern over the bank. Winds were fresh, decreasing to moderate (11 – 6 m/s) initially from the southwest, before veering westerly, then northerly. Atmospheric pressure was low, decreasing from 996 to 993 hPa during the survey.

The bank is about 12 nautical miles (22 *km*) long and 3 nautical miles (6 *km*) wide. Water depths varied between 40 – 48 metres either side, and north and south of the bank. Over the bank depths varied between 17 and 38 metres.

The temperature - salinity plot (Figure 53) shows temperatures varied from 4.4°*C* to 4.0°*C* between south and north along the bank (warmer water to the south) and a similar magnitude gradient existed from west to east, with 4.6°*C* water to the west, and 4.2°*C* to the east.Figure 54 shows the physical parameters gridded along the two transects. The south-north salinity plot suggests a column of marginally more saline water existed over the bank (7.55 *psu*, compared with 7.4 – 7.5 *psu* further from the crest). Combining this with the west-east transect, it appears that the saline water at the bank crest marked the shoreward limit of more saline offshore water. The gridded plot also suggests that there may be some southward flow along the bank's eastern flank, maintaining the density gradient between profiles 61 and 59. Stratification was strongest in deep water, with maximum stratification (0.001 – 0.004 $s^{-2}$) between 40 – 41 metres. Above this, the profiles were well mixed. Stratification in the surface layer and over the bank itself was at least an order of magnitude weaker, with the pycnocline occurring between the surface and 13 metres. Immediately over the bank surface, stratification appears to be slightly stronger than in the surrounding water at the same depth. This is contrary to what has been found at the previous banks.

Total nitrogen levels across the bank were fairly constant, between 18 and 23 $\mu M$. DIN was dominated by nitrate, though ammonium levels were significant (~25% of the DIN concentration) in deep water both north and west of the bank. Phosphorus (both DIP and total phosphorus) and silicate concentrations were also greater at depth at these stations (1 – 1.5 $\mu M$ and ~20 $\mu M$ repectively). Otherwise, these nutrients showed little variation either across the bank or with depth.

### Norra and Södra Midsjöbanken

These banks were sampled together, between 0105Z and 2030Z on the 15th January 2004. Sampling consisted of two east-west transects (one over each bank) of four stations each, and a single north-south transit covering both banks, consisting of eight stations. The north south transect extended about 55 nautical miles, while each east-west transect was about 25 nautical miles. Winds were initially fresh breezes from the northwest (9 – 10 *m/s*), then veered northerly and weakened to between 7 and 9 *m/s*. At the start of the Norra Midsjöbank sampling, the wind increased again to 10 – 11 *m/s*, before backing northwesterly again and weakening to 6 *m/s*. Atmospheric pressure increased steadily during the sampling, from 989 *hPa* at 0100Z to 999 *hPa* at 2030Z.

Each profile was very well mixed with depth. Warmest, and most saline, water was found at 0028, to the southwest. Moving eastwards towards the crest of the Södra Midsjöbank (indicated by the blue line in Figure 5) the profiles became fresher and cooler, before becoming warmer and more saline again just east of the 30 metre depth contour. Over the Norra Midsjöbank (the red line in Figure 5) a similar pattern exists, with colder and fresher water over the bank crest, although the whole transect was about 0.2$°C$ cooler than that over the Södra Midsjöbank. At the start of the south – north transect, the water was only slightly warmer and more saline than that found over the Södra Midsjöbank crest. Between the banks, at profile 0037, conditions were similar to profile 0028 (the southwestern-most profile) – relatively warm and saline. There was then a strong gradient to fresher, colder water towards the northern bank crest. North of the bank, the water was again warmer (by ~0.5$°C$ ) and slightly more saline (0.05 *psu* at the surface).

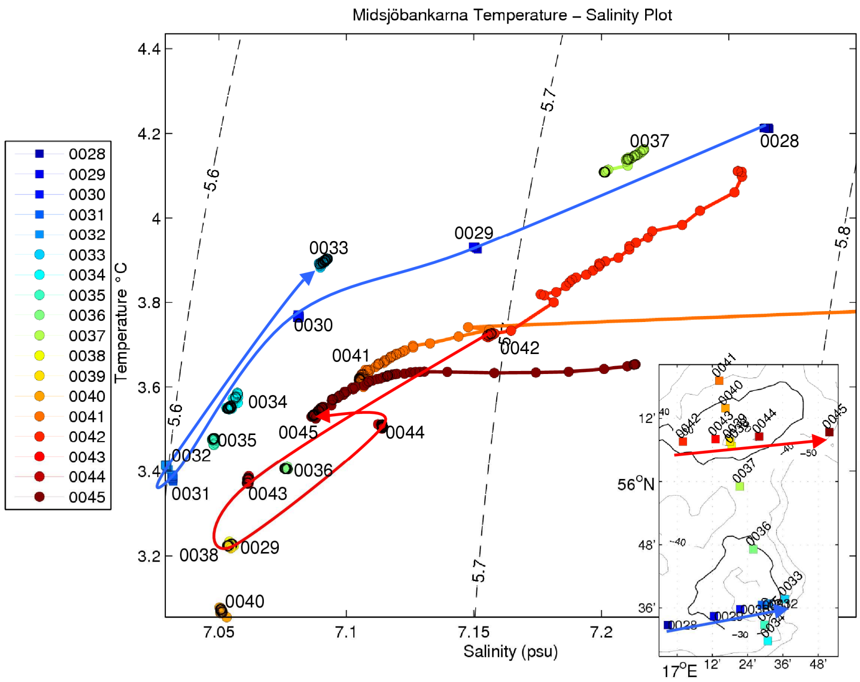


*Figure 5 Temperature Salinity diagram over both the Midsjö banks.*

Stratification was almost non-existent along the west-east profile across the southern bank. Maximum buoyancy frequencies here varied between $5 \times 10^{-6}$ and $5 \times 10^{-5}$ $s^{-2}$. Across the northern bank, stronger stratification was found to the west ($2 \times 10^{-4}$ $s^{-2}$ at 11 *dbar*, with an additional interface at 22 *dbar*) and east ($3 \times 10^{-4}$ $s^{-2}$ at 41 *dbar*). Over the bank itself, stratification was as weak as over the southern bank. Along the south – north profile, stratification was weak over the southern bank and even in the deeper water between the banks ($1 \times 10^{-4}$ $s^{-2}$ at 20 *dbar*). North of the Norra Midsjöbank the pycnocline was well defined at 35 *dbar* depth (salinity change of 1 *psu* and temperature change of 0.5$°C$ over 1 metre; buoyancy frequency of $9 \times 10^{-4}$ $s^{-2}$).

The weak stratification is reflected in the nutrient and oxygen concentrations, which show little variation with depth. Over the Södra Midsjöbank, total nitrogen concentrations were around 20 $\mu M$ and DIN (which was made up almost entirely of nitrate) concentration was about 3 $\mu M$. Concentrations were similar over the Norra Midsjöbank, though DIN included slightly higher levels of nitrite than over the southern bank. Total phosphorus concentrations were only slightly higher than DIP concentrations over the Södra Midsjöbank (around 0.7 and 0.5 $\mu M$, respectively), and showed little variation with depth. Across the northern bank (north of profile 0037) phosphorus concentrations reached 1 $\mu M$ (total) and 0.8 $\mu M$ (DIP). North of the bank, concentrations reduced again, to around 0.8 $\mu M$ (total) and 0.6 $\mu M$ (DIP). Silicate showed the same distribution, with higher values across the northern bank (about 16 $\mu M$ compared to around 10 $\mu M$ over the southern bank).

There was very little variability in oxygen concentration, with depth or position over the banks.

### Hoburg Bank

Hoburg Bank was sampled on the morning (0240Z – 1125Z) of 22$^{nd}$ October 2003. A strong breeze (11 – 14 *m/s*) blew from north of northeast, which increased to near gale (15 *m/s*) before weakening to between 6 and 11 *m/s*. Atmospheric pressure increased slowly during the 9 hours of sampling, from 1017 to 1020 *hPa*.

Along the west – east transect, densest water was found at the first profile (0632). Progressing across the bank, water became progressively warmer and fresher (and thus lighter) up to profile 0634. The last profile, 0635, is both cooler and more saline, being similar (at the surface) to profile 0638. It becomes progressively more saline along the north – south transect, starting at about 6.75 *psu* at profile 0636, and increasing to 7 *psu* at 0640. Temperature is fairly steady, above 10.2°*C* at all profiles between 636 (above 33 metres) and 640, with the exception of 0639. This profile lies just south of the bank crest, and appears very similar to profile 0633.

To the east and west of the bank, stratification was relatively strong (maximum buoyancy frequency of $1 – 2 \times 10^{-4} s^{-2}$) with the pycnocline coming at 35 metres. Above 35 metres, and over the bank itself, profiles were well mixed (peak buoyancy frequency between $5 – 15 \times 10^{-6} s^{-2}$). North of the bank (profile 0636) the pycnocline was also obvious at 35 metres, though the buoyancy frequency maximum came with the halocline at 25 metres.

The weak stratification was again reflected in the nutrient and oxygen concentrations, which showed only small variations with depth. Total nitrogen concentrations lay between 16 and 22 $\mu M$. DIN levels were around 0.3 $\mu M$, of which most was made up of ammonium. Total phosphorus concentrations were around 0.5$\mu M$, and DIP about 0.2 $\mu M$. Silicate concentrations were under 11 $\mu M$. Oxygen concentrations were above 7.2 *ml/l*, and saturation close to 100%.

### Knolls Grund

According to the chart, Knoll's Grund is a 15 km long, narrow bank lying northeast of Öland, and characterised by several 'tops' i.e. there is no well defined shallowest point. The sampling pattern consisted therefore of a long south – north section (two northern stations: 0695 and 0697; one central: 0699; three southern: 0701, 0702 and 0703), following the bank crest, and a shorter almost east-west transect (one station east of the central point: 0700; two to the west: 0696 and 0698) over what was thought to be the shallowest part. Sampling took place between 1815 and 2225Z on the 14$^{th}$ November 2003. Winds consisted of a steady light breeze (3 *m/s*) from the south west, and atmospheric pressure was steady at 1022 *hPa*.

Figure 85 shows the temperature salinity relation for these stations. Following the south – north transect, surface water became fresher, and slightly (0.1°*C*) warmer as the transect approached the bank crest. The freshest surface water was found at profile 0701, just south of the position of the east – west transect. Continuing northwards, the surface water became more saline again, though warmer, at the position of the transect (profile 0699) before cooling again north of the bank. Profiles 0696 and 0698, which made up the western side of the west to east transect were identical in upper 8 metres. Profile 0698 lay in a deeper hole situated in the middle of the bank. Both these stations and 0700 were more saline than 0699 over the bank crest, though there was little difference in temperature.

Strongest stratification was found at profile 0695, north of the bank. Here the halocline and thermocline occurred between 49 and 69 metres, which is quite typical for the deep basins in the Baltic Proper. Maximum buoyancy frequency associated with this profile was $4 \times 10^{-3}\ s^{-2}$. This contrasts with the weaker stratification over the bank (peak buoyancy frequencies from 1 – $5 \times 10^{-4}\ s^{-2}$). Weakest stratification was found at profile 700, which closely ressembled the surface (0 – 40 m) conditions further out in the West Gotland Basin.

DIN concentrations across the bank were less than 1 $\mu M$, with ammonium being the largest fraction, at least down to 40 metres. This is not uncommon for the time of year, and higher concentrations, and a greater proportion of nitrate, would be expected later in the winter. Total nitrogen concentration was around 18 $\mu M$. Phosphorus also showed little variation with position or depth above 40 metres. Total phosphorus concentrations were about 0.6 $\mu M$ above 40 metres, and DIP was about 0.35 $\mu M$. Higher values occurred in deep water north of the bank (profile 0695) where DIP made up almost all the total phosphorus, and concentrations reached 2.5 $\mu M$ at 60 metres. Silicate showed the same variability. Concentrations were around 12 $\mu M$ in the upper 40 metres, but almost reached 40 μM at 60 metres. Oxygen concentrations were around 8 *ml/l*, corresponding to a saturation of just under 100%, though profiles 0703, 0697 and 0695 showed minima just above the bottom at 35 m (90%), 50 m (75%) and 63 m (< 10%) respectively.

## 3.3 Circulation diagnosis from CTD profiles

Techniques to infer circulation patterns from density profiles in shelf seas have been around since at least the 1930's (Defant, 1961). Sheng and Thompson (1996) presented a method for predicting the circulation around a series of banks on the Canadian east coast. The method involves calculating the bottom density anomaly at each profile, relative to a mean bottom density, and then calculating the geopotential anomaly and resulting dynamic height field over the area of interest. An assumption of geostrophic balance (which may not be completely valid in the Baltic because of sensitivity to wind forcing) predicts that currents would follow the lines of equal dynamic height.

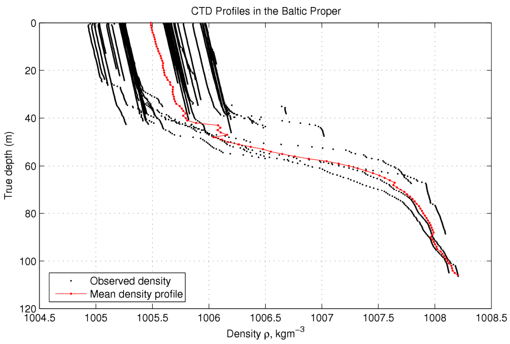


*Figure 6 Observed & mean density profiles around the Baltic Banks*

Figure 6 shows the observed and mean profiles from the banks in the central Baltic Proper (Knolls Grund, Hoburg Bank, Norra and Södra Midsjöbanks and Ölands Södra Grund). The bottom density from each profile was described in terms of the mean bottom density and an anomaly term. This separation also allowed the sea level to be written in terms of a mean dynamic height term, and a dynamic height anomaly.

Sheng and Thompson used 70 years of hydrographic data to calculate their mean bottom density. In this study, only those profiles obtained during the project were used, so it is debatable whether the results obtained represent 'normal' conditions.

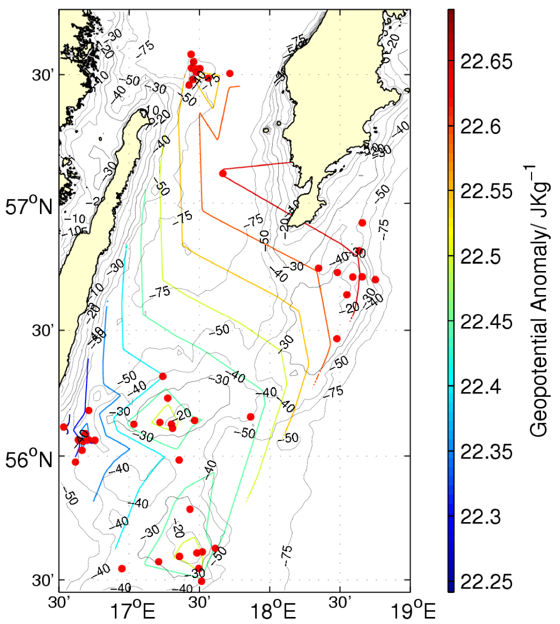


*Figure 7 Estimate of the geopotential anomaly in the southern West Gotland Basin*

Figure 7 shows the calculated geopotential anomaly based on the CTD profiles taken over the banks of the southern West Gotland Basin, gridded using a simple Delauney triangulation. The dynamic height field is plotted over the the bathymetry. The dynamic height associated with this field is an order of magnitude smaller than the geopotential anomaly – that is to say about 2.25 dynamic centimetres.

Over the Norra and Södra Midsjöbanks there are 'humps' of less dense water over the bank crests. These are of the order of 2 – 3 dynamic millimetres higher than the surrounding water. Similar, though smaller features are also visible over Knolls Grund and Ölands Södra Grund, though not over the Hoburg Bank.

To support a sea level gradient of this size (3 *mm* over 15 *km*) at this latitude requires a flow of about 1.5 *cm/s*. Assuming these features are maintained by geostrophic balance, circulation around each bank is to be expected. Similar analyses over Kriegers Flak and in the Kattegat failed to show similar structures over the bank crests, though this may be due to the small number (and distribution) of density profiles available to this study.

## 3.4 Impacts on Kattegat flora and fauna

Areas of the Kattegat suffer oxygen deficiency, particularly during late summer and autumn, when organic material from spring and summer plankton blooms is broken down. This seasonal oxygen deficiency can be exacerbated by stable atmospheric conditions, which limit horizontal water exchange. The permanent stratification is also enhanced by these stable conditions, which further hinders vertical exchanges of oxygen. Both mechanisms prevent the introduction of fresh oxygen to the bottom water. The resulting oxygen deficiency can be so severe as to suffocate benthic organisms and even cause fish kills over large areas. The areas worst affected by these hypoxic (and sometimes anoxic) events are usually relatively deep, though shallow areas with particularly poor water exchange and/or local nutrient inputs, such as Skälderviken, are also vulnerable. Oxygen deficiency primarily affects water below the pycnocline, which comes at 15 metres in the Kattegat. It is reasonable to suppose that these events affect biota below 15 metres on the offshore banks in the Kattegat.

During late summer 2002, the Kattegat and Belt Sea suffered what is believed to be its worst ever oxygen deficiency event, at least for the past 30 years (Ærtjeberg et al, 2003). In February – March and July – August 2002, run-off from land was particularly high and delivered large amounts of nitrogen to the area (despite the annual total nitrogen load being close to normal). The high nitrogen loads led to particularly strong plankton blooms, observed both through primary production measurements and observations of chlorophyll-a concentration. The impact of this enhanced productivity was exacerbated by calm atmospheric conditions during late summer which prevented re-oxygenation of the bottom water by horizontal advection and vertical mixing. Figure 8 shows the maximum extent of the 2002 oxygen deficiency (Ærtjeberg et al, *op. cit.*). This plot indicates that while the deeper areas of the southern Kattegat were affected, the shallower areas, for example around Stora Middelgrund, escaped.

Figure 9 shows ten years of oxygen data from the hydrographic station at Anholt E, just north of Stora Middelgrund. This shows that since autumn 1998, oxygen concentrations as low as 3 *ml/l* extended to within 20 metres of the surface, and so have affected large areas of the bank. In autumn 2001 and 2002, oxygen saturation at 20 metres fell below 50%. The minimum depth over Röde Bank is 25 metres, so the whole bank was affected. Those creatures able to remove themselves from the area would probably have done so. It is likely that many bottom living creatures would have been able to tolerate these conditions however, and were probably only slightly affected. A similar figure for the station north of Fladen (Figure 10) indicates that 50% saturation is restricted to depths greater than 30 metres, so do not affect the shallower parts of the bank under investigation in the current study. Those deeper parts of the bank are likely to be affected however.

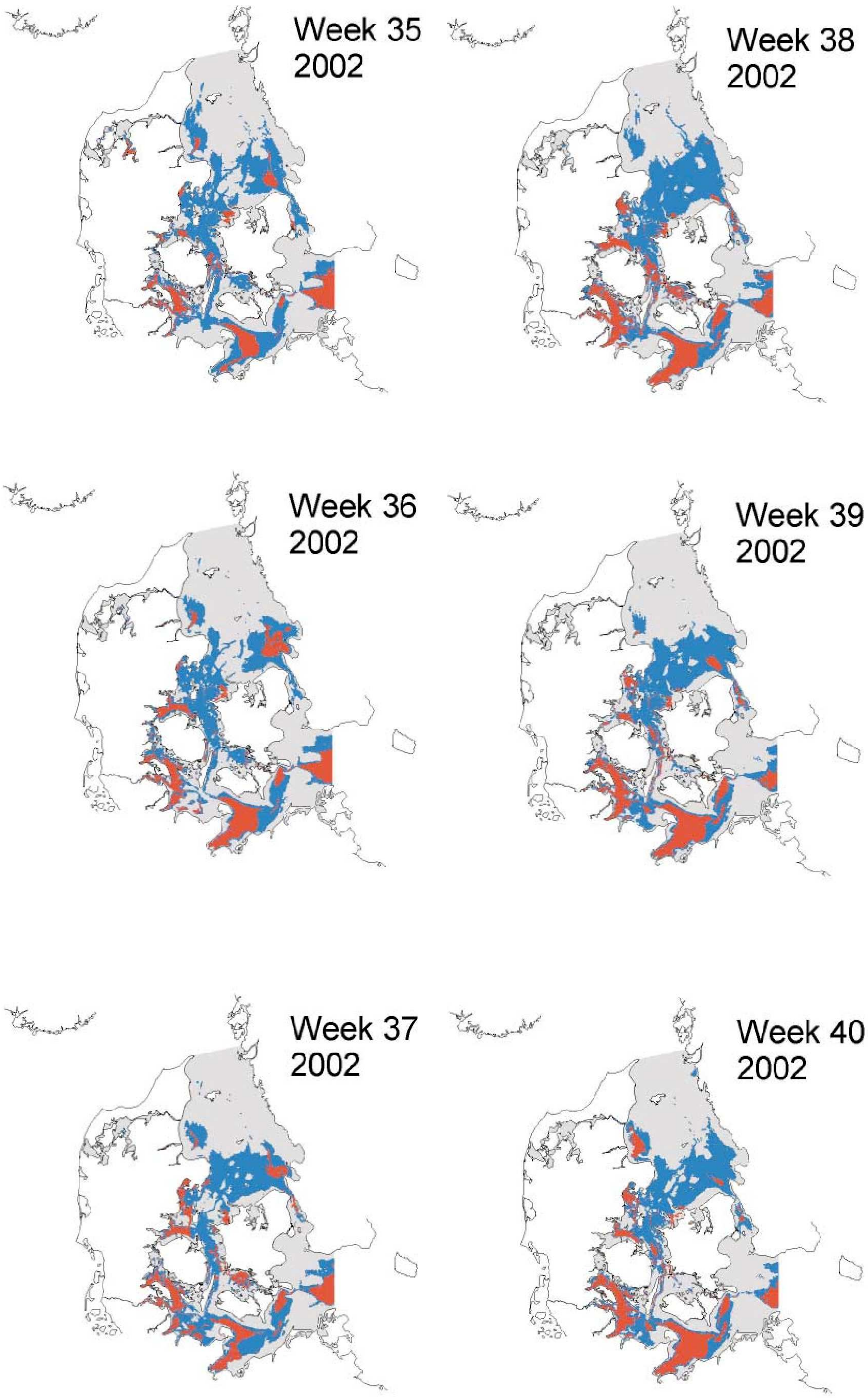


*Figure 8 Maximum extent of the 2002 Oxygen Depletion (from Ærtjeberg et al, 2003)*

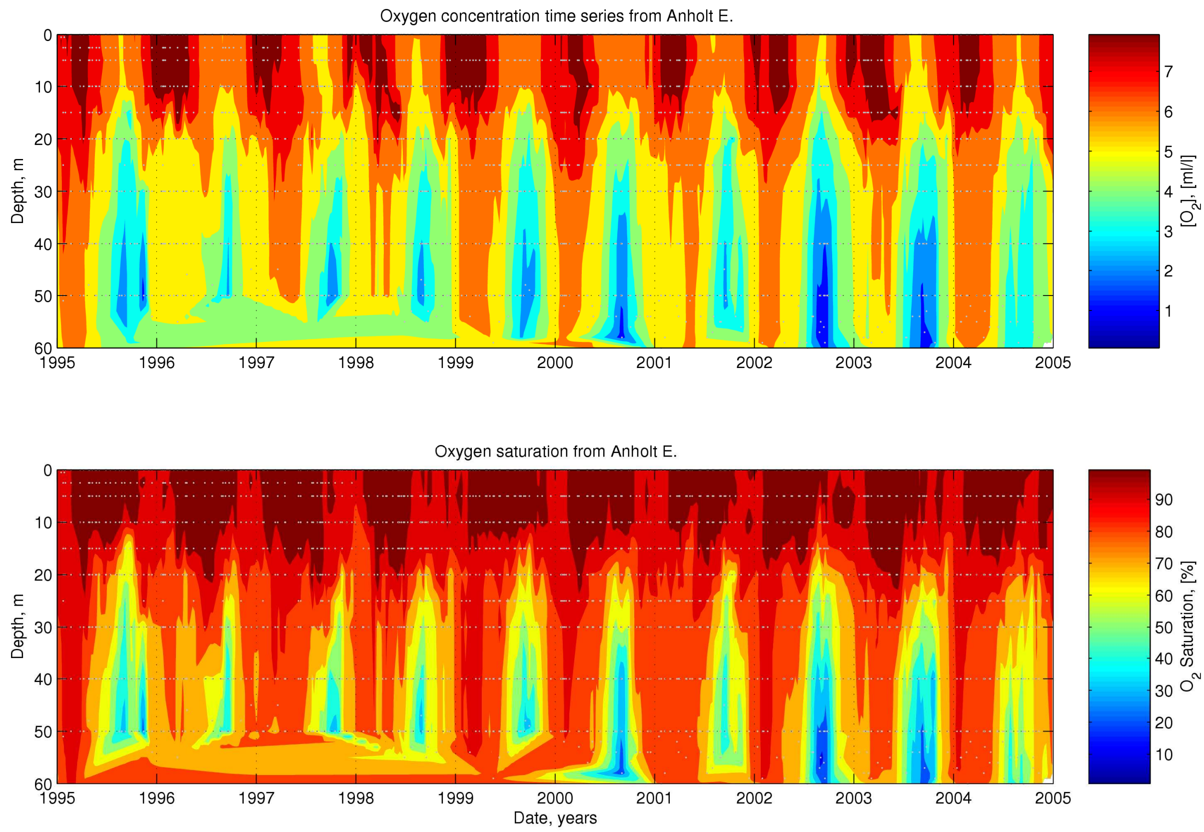


*Figure 9 Time series of oxygen concentration and saturation from Anholt E.*

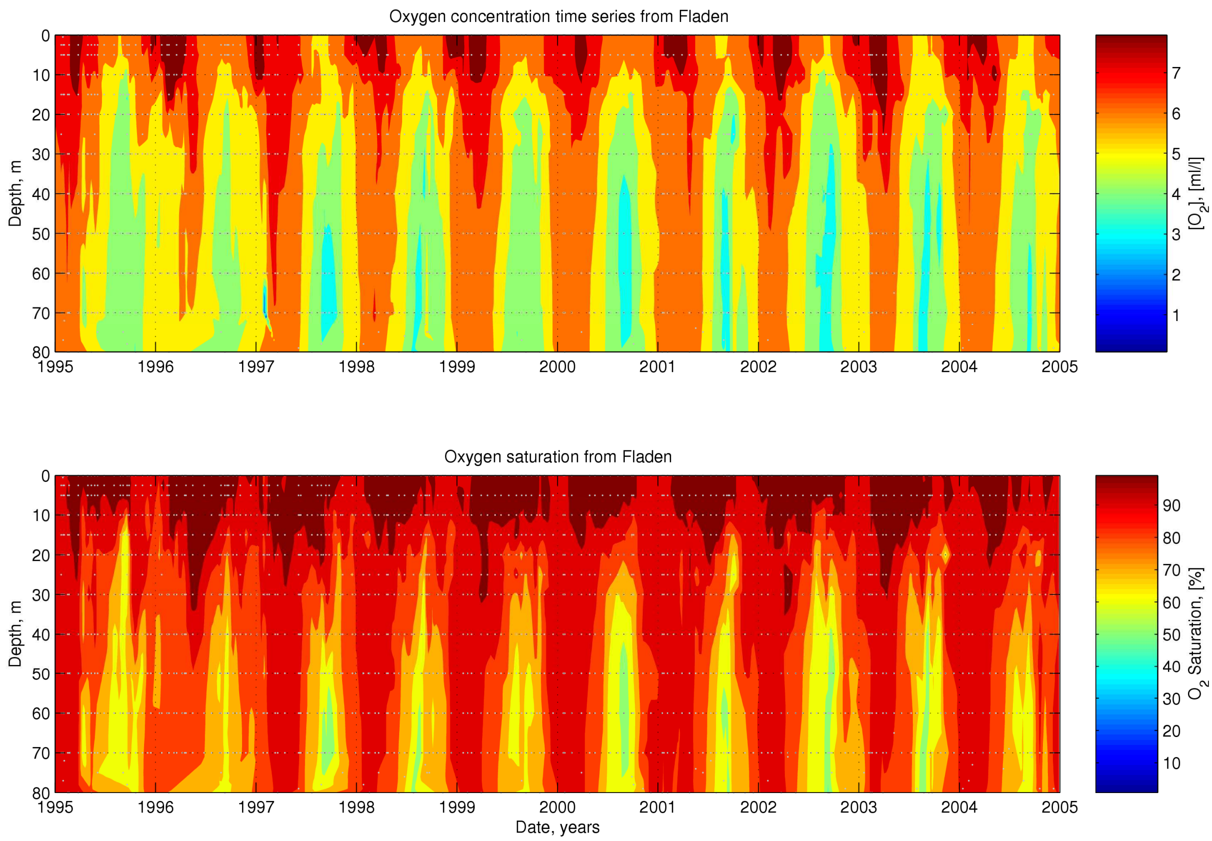


*Figure 10 Time series of oxygen concentration and saturation from Fladen*

# 4 Model data

In addition to the ship observations made both during this project and earlier, SMHI has archives of model data. Discussions at project steering meetings indicated that project partners were interested in the effect of the banks on currents and circulation (and whether this had implications for the retention of fish larvae in the vicinity of banks) and also on wave climate over the banks, and the implications of this for both bottom sediment type and transport.

## 4.1 Currents and circulation

Analysis of CTD profiles (Section 3.3) showed that density gradients exist across several banks, and that (assuming geostrophic balance) circulation patterns would be expected to exist around several banks. Additional CTD profiles, or current meter profiles (for example, from an Acoustic Doppler Current Profiler) would allow further investigation of any circulation patterns. As such data were not available to this study, current data were extracted from the High Resolution Model of the Baltic (HIROMB), to describe the current patterns across the banks, and to see if any such circulation was apparent.

HIROMB is SMHI's 3D ocean circulation model. The model domain covers the entire Baltic, as well as the North Sea and English Channel, with 12 nm resolution. Higher resolution, nested versions (3 nm and 1 nm) are run for the Baltic, as well as the Kattegat and Skagerrak. The model is run daily, providing 6 hourly predictions of sea levels (storm surges), ice extent, thickness and movement, as well as temperature, salinity and current velocity for up to 24 levels. The model is driven with tidal information at the offshore boundaries, and with meteorology from SMHI's atmospheric model. This study makes use of current data from 4, 8, 12, 18, 24, 30, and 40 metres, calculated during 2004. Data from 2004 were chosen so as to benefit from the latest model improvements.

Data were processed to give the annual mean current, averaged through the upper 40 metres. The results of this averaging are shown in Figure 11. In the Kattegat (Figure 11a), the Baltic outflow is clearly visible from both the Belt Sea (bottom left) and the Sound (bottom right). The outflow through Öresund follows the Swedish coast, while that from the Great Belt comes up from south of Anholt as a relatively broad stream, with some meanders. The two currents coalesce near Lilla Middelgrund, becoming a broad northward stream.

The effect of the bathymetry on the mean current is apparent south and east of Stora Middelgrund, where there appears to be some recirculation in an area of otherwise weak flows. Similarly, the ridge between Fladen and the Swedish mainland, which is about 30 metres deep, is sufficient to cause recirculation.

Near Kriegers Flak (Figure 11b), separation of the Baltic outflow and the anticlockwise circulation in the Arkona Basin are seen clearly, with most water flowing out towards the Darss Sill or returning along the south. and some circulation in the northwest close to the entrance to Öresund. The effect of the bank appears to be to split the outflowing water, with intense, southward currents on the bank's eastern flank, and weaker flows over the crest. Similar funnelling effects in deep water are apparent in the western Baltic Proper (Figure 11c), where the Baltic current flows down the Swedish east coast, before splitting north of the Midsjö Banks. This water directed between the Norra Midsjö bank and Hoburg Bank returns to the south eastern Baltic, while that which goes between the Norra Midsjö Bank and Ölands Södra Grund follows the Swedish coast. Over the banks themselves, the mean currents are relatively weak. South of the banks, the eastward current along the Polish coast appears to have some interaction with the Baltic outflow, resulting in a gyre to the west of the Södra Midsjö Bank. This gyre may be a permanent feature. Voss et al (1999) modelled the advection of cod larvae from the central Bornholm Basin. After 21 days simulation of 1991 conditions, a significant proportion of larvae were found clustered in the gyre.

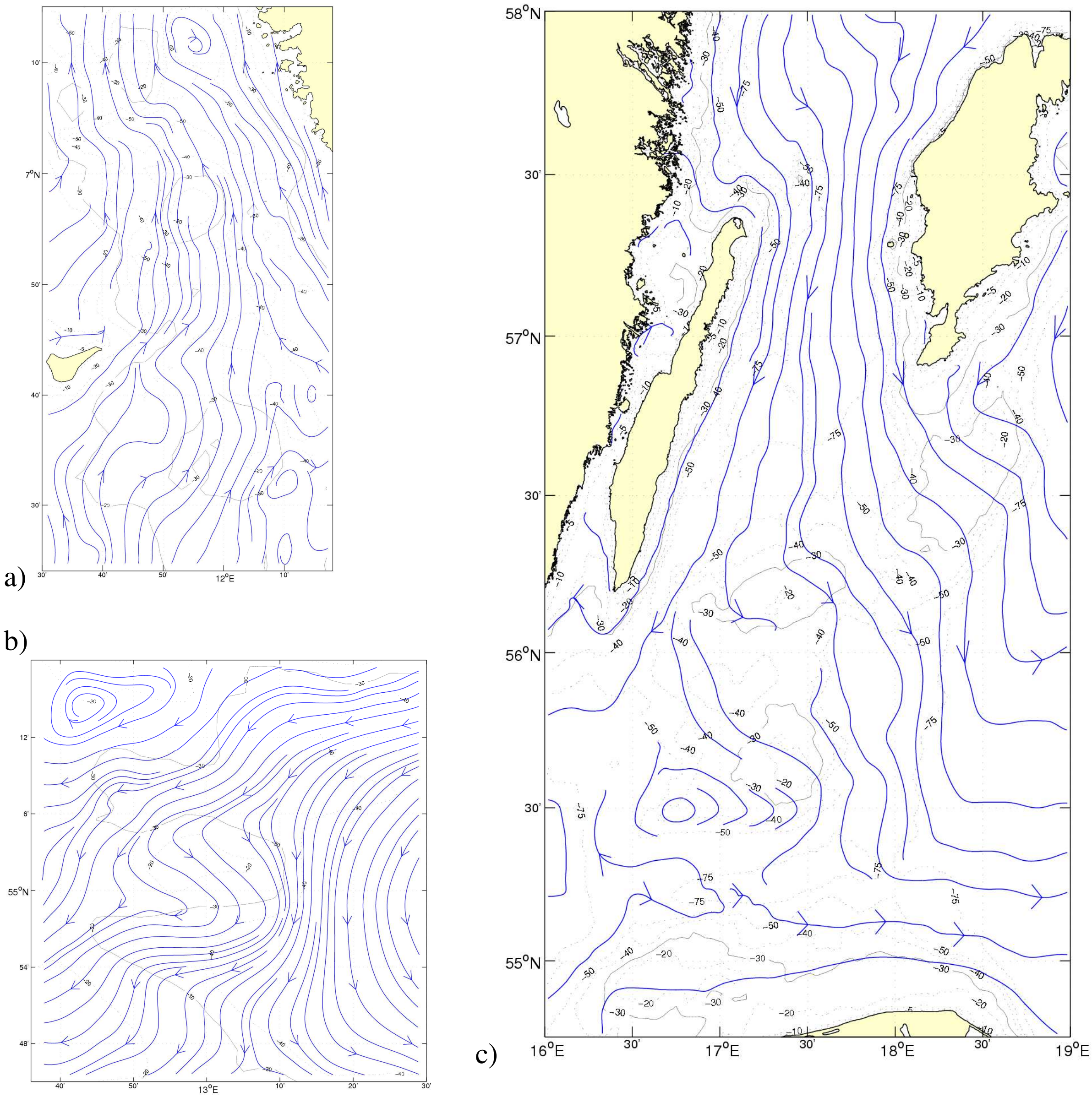


*Figure 11 Annual mean, depth integrated (0 – 40 metres) stream function from HIROMB, showing the large scale circulation for the Kattegat (a), Kriegers Flak (b) and Baltic Proper banks (c). Depth contours are shown in grey.*

Kinetic energy indicates flow intensity. Separated into parts describing the mean and fluctuating components, it is useful to describe both areas of steady flow, and those areas affected by short term disturbances such as eddies. The apportionment of energy between these two modes indicates their relative intensity. The monthly mean kinetic energy is defined as:

$$k.e._{mean} = \frac{1}{2}\left(\bar{u}^2 + \bar{v}^2\right) \qquad \text{Equation 1}$$

while the eddy kinetic energy, that is the energy associated with fluctuations in the flow, is given by:

$$k.e._{eddy} = \frac{1}{2}\left(\sigma_u^2 + \sigma_v^2\right) \qquad \text{Equation 2}$$

$\sigma_u$ and $\sigma_v$ are the standard deviations of the zonal and meridional ($u$ and $v$) currents respectively.

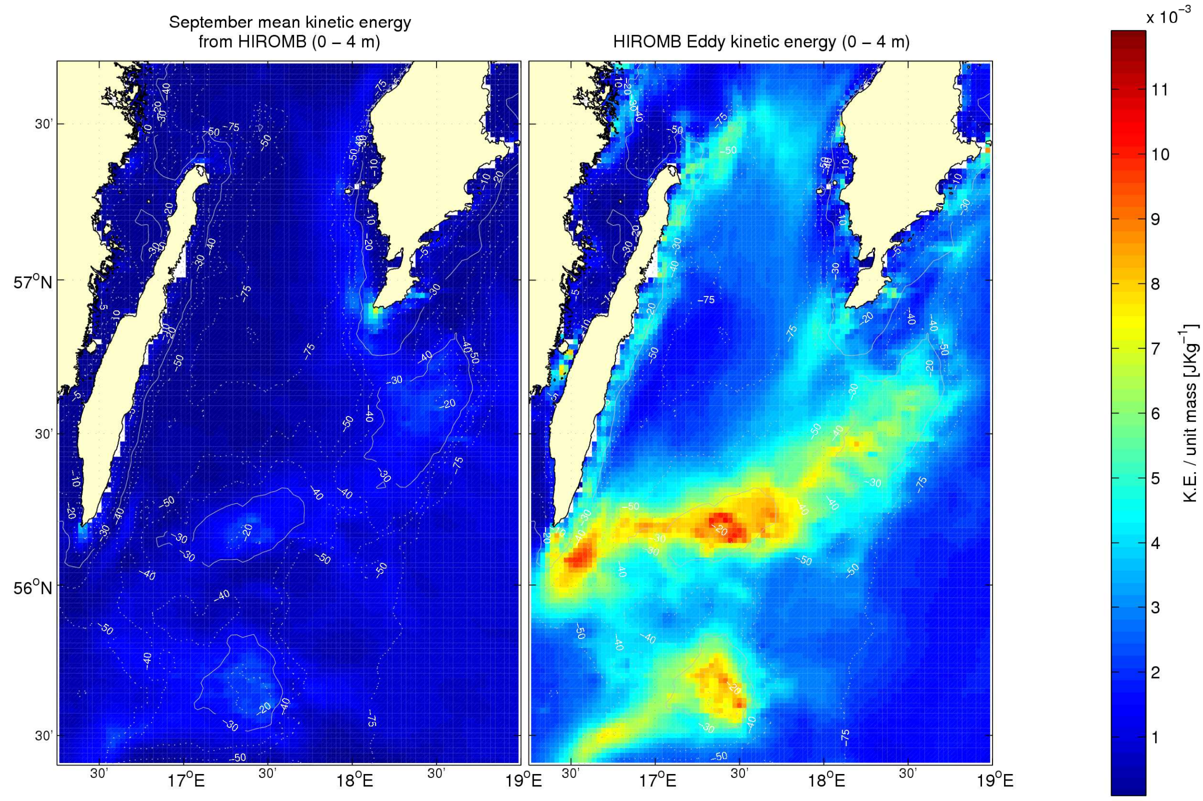


*Figure 12 Mean (left) and eddy (right) kinetic energy (per unit mass) from HIROMB surface data, September 2004. The bathymetry is indicated by the grey contours.*

Figure 12 shows the mean and eddy kinetic energy from HIROMB's surface layer, averaged over September 2004. Other months show a similar picture, though absolute energy levels vary. Highest levels occur in winter, lowest in summer. The figure shows that there is more energy associated with the fluctuating, rather than mean, flows, which is not surprising, given that wind forcing is particularly important in the surface, and is not steady. Despite this, at the southern tips of Gotland and Öland there are local high (mean) energy areas. An area of lighter colour extends down the west coast of Gotland, and snakes over the Hoburg Bank and both the Norra and Södra Midsjöbanks – with some local maxima over the bank crests. Another area appears just east of the southern tip of Öland - over Ölands Södra Grund. The mean picture shows that steady currents are more intense in the shallow water over the banks, as well as at the southern tips of the islands. This is most likely due to the mean flow being accelerated around headlands and across the shallower water.

The eddy kinetic energy distribution is similar. High energy areas occur over the Södra Midsjö Bank, and also stretch from Ölands Södra Grund, across the Norra Midsjö Bank as far as the Hoburg Bank. The amount of energy in these areas is three times that associated with the mean flows. These fluctuating currents are likely to be responses to wind forcing over short timescales, and so not in geostrophic balance. Differences are the maxima that occur along the Öland coast, as far as Knolls Grund, and the absence of eddy kinetic energy along the west coast of Gotland.

A similar situation exists over Kriegers Flak, with higher mean kinetic energy over the bank itself, and to the north, close to Drogden. Eddy kinetic energy levels were around three times greater than those associated with the mean flow, with maxima over the bank and south of Drogden, but with most energy associated with the area south of the bank, close to the Darss Sill. In the Kattegat, energy levels were about four times greater than over Kriegers Flak. Maxima in the mean flow occurred at the tip of Anholt, over Fladen (and to a lesser extent, over Stora and Lilla Middelgrund) and along the Swedish coast. Maxima in the eddy kinetic energy occurred at the same locations. Anholt's eastern tip and the area extending south-westward from Fladen (Kattegat front) were far more energetic than the areas over the banks.

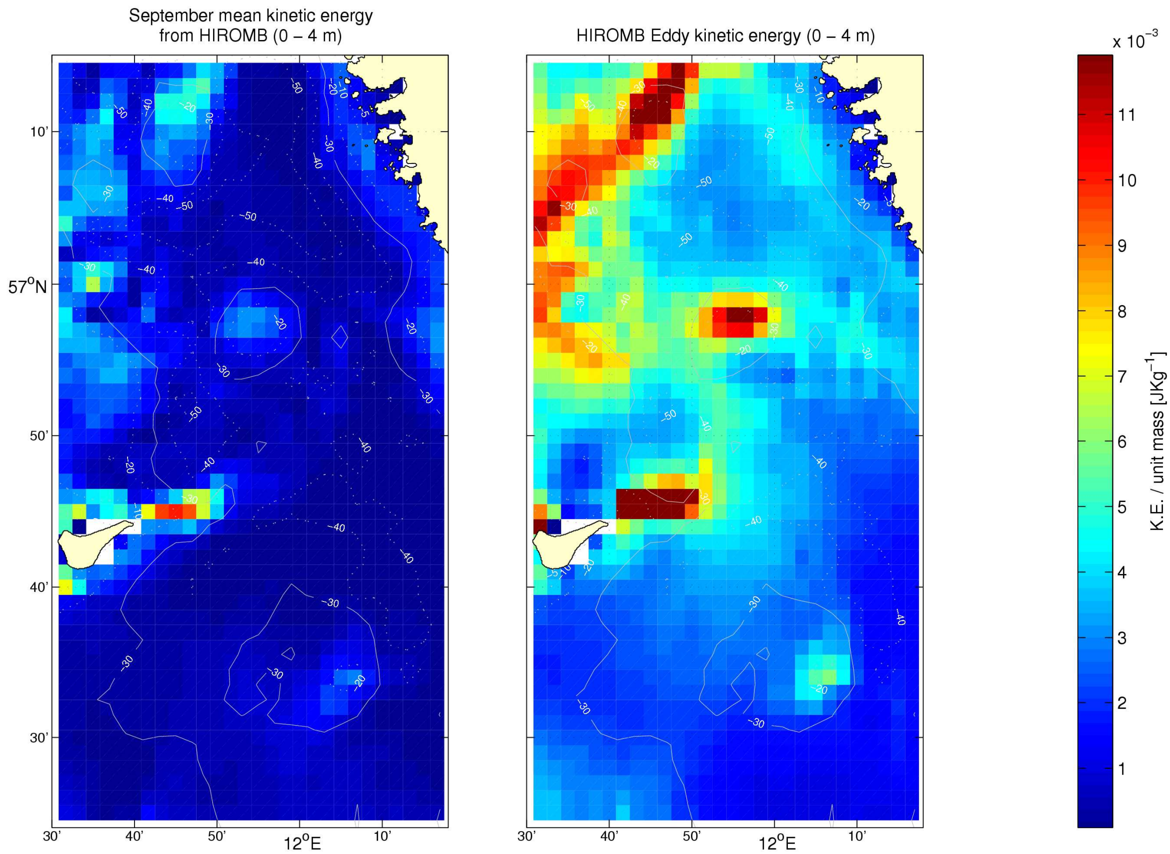


*Figure 13 Mean (left) and eddy (right) kinetic energy (per unit mass) from HIROMB surface data,for the Kattegat September 2004. The bathymetry is indicated by the grey contour. Higher kinetic energy is apparent over Stora and Lilla Middelgrund, Fladen, and around Anholt.*

## 4.2 Wave conditions

Bottom substrate is of great importance in determining the range of plant and animal species that colonise shallow areas. A substrate consisting of boulders or bare rock may be colonised by clinging organisms, while softer materials, such as sands and mud provide suitable habitats for burrowing organisms. Substrate is governed by a number of factors, including sediment availability. Whether sediment deposited over an area remains in place is governed by the wave and current climate.

Linear wave theory gives a very good description of non-breaking wave conditions. Using linear wave theory, it is possible to derive water movements underneath waves. Figure 14 shows the elliptical water movements under waves in both intermediate/shallow water (left) and deep water (right). Where the water is deep relative to the wavelength (depth is more than twice the wavelength) the elliptical water movements become almost circular, and their diameter decays exponentially with increasing depth, so that the effect of the surface wave on the bottom is nil. In shallower water, the ellipses are flatter – indicating that the horizontal current speeds are greater than the vertical. These ellipses also decay in size below the surface, and become flatter (that is to say, the vertical velocity falls off more quickly than the horizontal). At the sea floor, the wave action is felt as a simple to-and-fro horizontal motion.

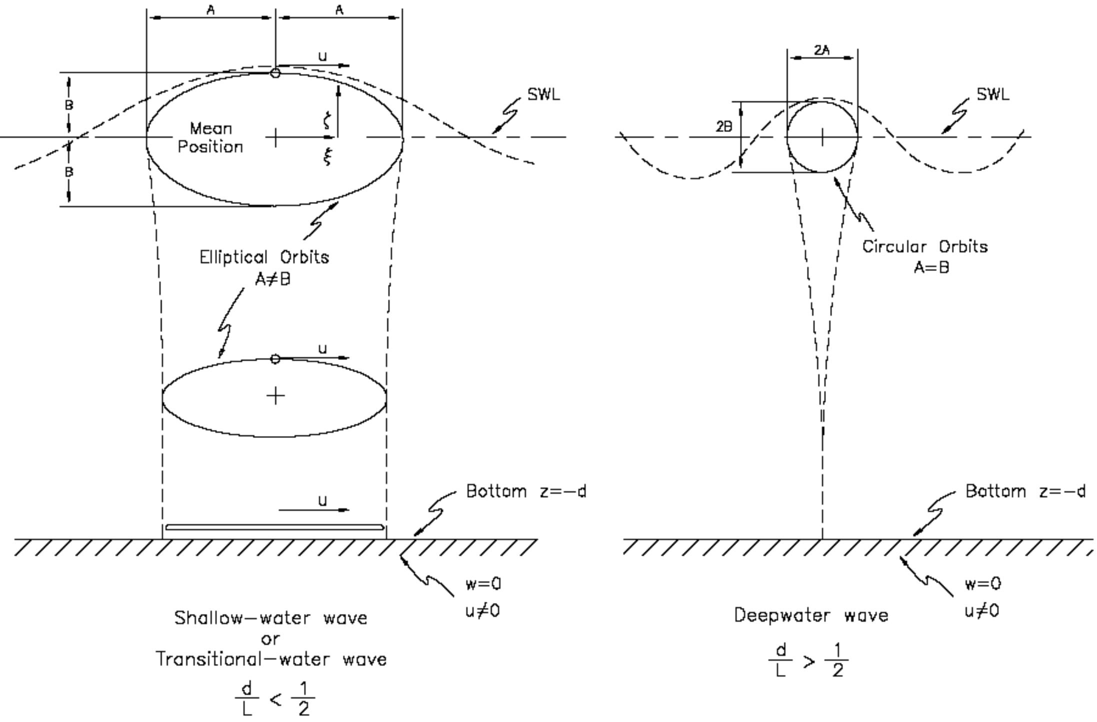


*Figure 14 Water movements under waves in intermediate/shallow (left) and deep (water) respectively (from Coastal Engineering Manual, Part II, Chapter 1)*

The bottom currents under waves can disturb sediment, or remove material deposited on the bottom. While simple linear theory suggests that any material would simply be move backwards and forwards about its initial position, bursts of turbulence can reach the bed as the water changes direction, lifting material up into the water column, where it can be moved by currents . In addition, there is some mass-transport under waves (Stokes' drift), which can transport material (this is a known limitation of linear wave theory). Ferentinos and Collins (1980) suggest that the wave climate may be the limiting factor in bank height, at least in tidal waters. Jönsson (2002) discusses the affect of varying wave climate in the Baltic on sediment resuspension and transport.

The result of this is that in shallower water, wave-induced bottom velocities are greater than in deeper. Fine material can be removed which, if the removal rate is greater than the supply of new material, leads to a bottom made up of coarse material, or even exposed bedrock. Equation 3 gives the horizontal $u$ velocity $z$ metres above a seabed of depth $d$, due to a wave of height $H$ metres, a period of $T$ seconds, and a wave length of $L$ metres. The $\theta$ term is the phase of the wave, and $g$ the acceleration due to gravity (9.81 m/s$^2$). The equation shows that maximum horizontal velocities occur when the cosine $\theta$ term equals 1. At the seabed, the $z+d$ term equals zero, so the maximum bottom current can be written as in Equation 4.

$$u = \frac{H}{2}\frac{gT}{L}\frac{\cosh[2\pi(z+d)/L]}{\cosh(2\pi d/L)}\cos\theta$$ Equation 3

$$u_{\max} = \frac{gHT}{2L\cosh(2\pi\, d/L)}$$ Equation 4

SMHI runs an operational wave model for the North Sea and Baltic. This model, called HYPNE (Hybrid parametrical shallow water nested) has a resolution of 22 km over the North Sea, and 11 km in the Baltic. The model is run four times daily, forced with winds calculated by SMHI's atmospheric model, HIRLAM, and results are archived at SMHI. HYPNE has been validated against several years of wave data collected at Almagrundet, Ölands Södra Grund, Oskarsgrundet, Trubaduren & Fladen (Lindquist, 1996), and gives a reasonable representation of wave conditions in the Baltic. The model is not so successful at reproducing wave spectra at very low wind conditions, but has been very useful in predicting wave conditions in storms.

To calculate the level of wave disturbance over the offshore banks, five years of data were extracted from the HYPNE archive (1999 - 2004). With a grid resolution of 11 km, representation of the wave field over smaller banks is not good. Wave heights in shallow water are underestimated, though so is wave breaking, direction changes and focussing effects[3]. Despite these limitations, the data are adequate to give an idea of water movements over the seabed, and the stresses exerted on the bed that affect sediment and biota.

Time series of significant wave height[4] $H_s$ and $T_p$, the corresponding spectral peak period, were plotted for each grid cell overlying a bank. From these time series, individual storm events were identified, and scatter plots showing the distribution of $H_s$ and $T_p$ produced. A scatter plot shows the distribution and frequency of the various wave height/period combinations. Data from 2003 were compared with data from the previous four years, which indicated that the period chosen was reasonable 'typical'. Maximum bottom orbital velocities were calculated using Equation 4, for each wave height/period combination identified in the scatter plot, for six different bottom depths ranging from 5 to 30 metres. The frequency of occurrence of each current strength at each depth was calculated, and is presented in Table 2 (for the Kattegat) and Table 3 (Baltic Proper).

Highest orbital velocities occur in shallow water, and can exceed 1 m/s during 30% of the time in 5 metres of water. Over the shallowest parts of Fladen, they can even exceed 2 m/s. In 10 metres, these extremes are less frequent – perhaps 1 – 2% of the time. In the Kattegat, wave influence is marginally weaker than over the banks of the central Baltic. The mildest wave climate is over Kriegers Flak and Öland's Södra Grund, because the short fetch lengths don't permit the same degree of wave growth as over the other banks. This could be reflected in a finer sediment cover over these banks.

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[3] To calculate wave heights and directions for design applications, where greater accuracy is required, SMHI uses *in-situ* measurements and/or data from numerical models run at high resolution (for example SWAN or even 'mild-slope' –based models).

[4] Significant wave height is traditionally defined as the mean height of the highest $^1/_3$ waves, and is denoted by $H_S$ or $H_{1/3}$. More recent spectral wave analysis methods and models, use $Hm_0$, obtained by integrating the wave energy spectrum to give the zeroth moment. $H_s \approx Hm_0 = 4\sqrt{m_0}$

# 5 Discussion

Each bank was visited once only between the autumn of 2003 and spring 2004. How typical are the measurements taken, and are they representative of the general conditions over the banks? The first part of this question is straightforward to answer where the profiles taken over the banks were supplemented with data from those stations in SMHI's normal monitoring programme. In the southern Kattegat, the high frequency station Anholt E. was taken at the same time as Stora Middelgrund and Röde Bank. Surface temperature and salinity and inorganic nutrients were very close to the 10 year average for the time of year, though silicate levels were high. Close to Kriegers Flak, data from BY1 shows that these data were also typical for the time of year.

Whether the data are representative of the conditions across the banks is slightly more difficult to justify. The restriction to 9 stations across each necessitated a compromise between areal coverage and resolution. The outer stations were necessary to relate the bank conditions to those existing in the adjoining basin (and so were not always limited to 30 metres depth), while the inner ones were an attempt to capture the detail of the hydrography across each bank. In general this appears to have worked reasonably, and demonstrated variations in water properties across the banks. Exact positions of fronts and gradients over the banks are not possible to ascertain with such coarse sampling, however. Knoll's Grund and Hoburg's Bank are examples where the approach was less successful. Knoll's Grund was very long, with many shallow areas along the ridge. The sampling used treated the bank as a simple structure, though a higher density sampling scheme (more stations) would be necessary to understand the flows around all the separate parts of the bank. The Hoburg Bank covers a very large area within the 30 metre depth contour, and has been poorly surveyed – as the whole area is a danger to shipping. Those charts available indicated that the northern end of the bank was a distinct, shallow 'top', and it was decided to concentrate on this area. The area to the south did not appear to be a homogenous region, more a network of channels and shallows. Plotting the sampling stations relative to the current 'best available' gridded bathymetry (Seifert's 2001 bathymetry) suggests (wrongly) that the observation stations lie to the north of the bank.

At some banks the surface nutrient levels were clearly still affected by summer phytoplankton activity, while at others it was clear that 'winter' conditions prevailed. The relative differences between individual profiles across a bank are still useful, however, and it is possible to see, for example, high near-bottom nutrient concentrations even over bank crests.

Gridding the CTD profiles clearly shows horizontal density gradients across the banks. Water movement is necessary to maintain these gradients. Analysis of the CTD profiles (following Sheng and Thompson, 1996) collected south and west of Gotland suggested that locally less dense water existed over the crests of Knoll's Grund, Ölands Södra Grund and the Midsjö Banks. This causes a variation in the dynamic sea surface height which requires a weak circulation to support it. Similar features were not visible at Kriegers Flak, though in the Kattegat the density changes are sufficiently large, for example across Röde Bank (Figure 31) and Stora Middelgrund (Figure 38) to imply the existence of a similar mechanism.

Despite the existence of the density gradients across the banks, and the circulation patterns implied by the Sheng and Thompson analysis, the gridded temperature and salinity fields do not indicate the existence of any particular 'bank water' trapped over bank crests by the circulation. Analysis of modelled current data from HIROMB also failed to show the existence of any permanent bank circulation in the residual (mean) current fields (Figure 11), though it did show the effect of the banks on steering the the mean flow, directing it into the deeper channels around the banks. The magnitude of these mean currents, associated with the permanent large scale circulation, is small. Of greater importance are the short term currents forced by the wind. These press water up over the banks, where the restricted depth causes the current speed to increase. These stronger currents found across the banks have implications for the transport of nutrients past filter feeders as well as for the resuspension of fine sediment and organic detritus. The impact of the strong oscillatory currents from wave activity reinforces the effects of wind induced currents, and indeed may be more significant in resuspending material over the bank crests, and allowing material to be transported away from the banks.

Over the bank sides in the Kattegat, stratification was weaker than away from the bank, in the middle of the flow. Over the bank crest, the situation is less clear. Across Fladen, the west – east profile showed the shallowest part of the bank to be a local region of weak stratification, while the shallowest part of the north-south profile remained strongly stratified. Lilla Middelgrund's crest was also well stratified (a west – east transect) while Röde Bank was more weakly stratified across the crest. Stora Middelgrund retained strong stratification immediately above the crest, though there was a well-mixed region several metres above this, before the larger scale stratification became apparent. Over Kriegers Flak, the entire bank area was poorly stratified (low buoyancy frequency) compared to the surrounding water. Over the remainder of the banks however, the situation was very similar to the Kattegat banks, with a small, localised region of stratified water immediately over the bank crest, while over the flanks the water was poorly stratified.

# 6 Conclusions

Hydrographic conditions over the offshore banks sampled are more complex than simply the upper part of the conditions in the deep water basins. The banks influence the large scale circulation. The large scale flows are diverted through the deeper channels between banks.. Mixing is enhanced immediately above over the sides of the banks, though over the bank crest water often remains stratified. There are strong density gradients across the banks, which influence circulation, though these may be part of larger frontal systems (for example, the Kattegat front between Fladen & Skagen). Surface currents across the banks are intermittent and intense compared to the adjacent deep water. This, coupled with the effect of waves, should lead to the frequent resuspension of fine material, including organic detritus.

Nutrient concentrations across the banks are similar to those found in deeper water, though higher concentrations of some nutrients (e.g. silicate, and occasionally phosphate) occur immediately above the bottom, even in the shallow water close to the bank crests. Oxygen saturation immediately above the bottom is frequently lower than in water of the same depth away from the banks. The shallow depths over the banks suggests that they are not usually affected by oxygen deficiency in the Kattegat, even during late summer and autumn. It should be noted that this finding is based on measurements taken adjacent to, rather than directly over, banks however.

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[1] Rossby Centre, SMHI [2] James Rennell Division, Southampton Oceanography Centre, [3] Department of Meteorology, Stockholm University

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# 9 Figures and tables

| | Fladen | | | | | | Lilla Middelgrund | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Bottom Depth (metres) | | | | | | Bottom Depth (metres) | | | | | |
| $U_{max}$, [m/s] | 5 | 10 | 15 | 20 | 25 | 30 | 5 | 10 | 15 | 20 | 25 | 30 |
| 0.00 - 0.25 | 7 % | 30 % | 55 % | 77 % | 94 % | 99 % | 5 % | 37 % | 61 % | 84 % | 98 % | 98 % |
| 0.25 - 0.50 | 22 % | 32 % | 36 % | 22 % | 6 % | 1 % | 31 % | 29 % | 31 % | 15 % | 2 % | 2 % |
| 0.50 - 0.75 | 16 % | 20 % | 7 % | 1 % | | | 11 % | 19 % | 6 % | 2 % | | |
| 0.75 - 1.00 | 20 % | 16 % | 1 % | | | | 21 % | 13 % | 2 % | | | |
| 1.00 - 1.25 | 13 % | 1 % | | | | | 16 % | 2 % | | | | |
| 1.25 - 1.50 | 16 % | | | | | | 14 % | | | | | |
| 1.50 - 1.75 | 4 % | | | | | | | | | | | |
| 1.75 - 2.00 | | | | | | | 2 % | | | | | |
| 2.00 - 2.25 | 1 % | | | | | | | | | | | |

| | Röde Bank | | | | | | Stora Middelgrund | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Bottom Depth (metres) | | | | | | Bottom Depth (metres) | | | | | |
| $U_{max}$, [m/s] | 5 | 10 | 15 | 20 | 25 | 30 | 5 | 10 | 15 | 20 | 25 | 30 |
| 0.00 - 0.25 | | | | 89 % | 98 % | 98 % | | 38 % | 62 % | 76 % | 95 % | 98 % |
| 0.25 - 0.50 | | | | 10 % | 2 % | 2 % | | 24 % | 26 % | 22 % | 5 % | 2 % |
| 0.50 - 0.75 | | | | 1 % | | | | 24 % | 10 % | 2 % | | |
| 0.75 - 1.00 | | | | | | | | 12 % | 2 % | | | |
| 1.00 - 1.25 | | | | | | | | 2 % | | | | |

*Table 2Frequency of different wave orbital velocities with bottom depth, based on Hypne data, for the four Kattegat banks.*

**Kriegers Flak**

| $U_{max}$, [m/s] | Bottom Depth (metres) 5 | 10 | 15 | 20 | 25 | 30 |
|---|---|---|---|---|---|---|
| 0.00 - 0.25 | | | 74 % | 96 % | 100 % | 100 % |
| 0.25 - 0.50 | | | 25 % | 4 % | | |
| 0.50 - 0.75 | | | 1 % | | | |

**Ölands Södra Grund**

| $U_{max}$, [m/s] | Bottom Depth (metres) 5 | 10 | 15 | 20 | 25 | 30 |
|---|---|---|---|---|---|---|
| 0.00 - 0.25 | | | | 80 % | 91 % | 96 % |
| 0.25 - 0.50 | | | | 16 % | 9 % | 4 % |
| 0.50 - 0.75 | | | | 4 % | | |

**Norra Midsjöbank**

| $U_{max}$, [m/s] | Bottom Depth (metres) 5 | 10 | 15 | 20 | 25 | 30 |
|---|---|---|---|---|---|---|
| 0.00 - 0.25 | | 11 % | 41 % | 63 % | 79 % | 89 % |
| 0.25 - 0.50 | | 30 % | 34 % | 25 % | 18 % | 11 % |
| 0.50 - 0.75 | | 31 % | 15 % | 10 % | 3 % | |
| 0.75 - 1.00 | | 17 % | 10 % | 1 % | | |
| 1.00 - 1.25 | | 7 % | | | | |
| 1.25 - 1.50 | | 4 % | | | | |

**Södra Midsjöbank**

| $U_{max}$, [m/s] | Bottom Depth (metres) 5 | 10 | 15 | 20 | 25 | 30 |
|---|---|---|---|---|---|---|
| 0.00 - 0.25 | | | 30 % | 58 % | 74 % | 88 % |
| 0.25 - 0.50 | | | 39 % | 30 % | 24 % | 11 % |
| 0.50 - 0.75 | | | 20 % | 11 % | 1 % | 1 % |
| 0.75 - 1.00 | | | 9 % | 1 % | | |
| 1.00 - 1.25 | | | 1 % | | | |
| 1.25 - 1.50 | | | | | | |

**Hoburg Bank**

| $U_{max}$, [m/s] | Bottom Depth (metres) 5 | 10 | 15 | 20 | 25 | 30 |
|---|---|---|---|---|---|---|
| 0.00 - 0.25 | | 22 % | 45 % | 61 % | 76 % | 88 % |
| 0.25 - 0.50 | | 27 % | 28 % | 27 % | 18 % | 12 % |
| 0.50 - 0.75 | | 19 % | 15 % | 10 % | 6 % | |
| 0.75 - 1.00 | | 18 % | 10 % | 1 % | | |
| 1.00 - 1.25 | | 7 % | 1 % | | | |
| 1.25 - 1.50 | | 6 % | | | | |

**Knolls Grund**

| $U_{max}$, [m/s] | Bottom Depth (metres) 5 | 10 | 15 | 20 | 25 | 30 |
|---|---|---|---|---|---|---|
| 0.00 - 0.25 | | 41 % | 59 % | 78 % | 87 % | 90 % |
| 0.25 - 0.50 | | 25 % | 25 % | 13 % | 9 % | 10 % |
| 0.50 - 0.75 | | 17 % | 9 % | 7 % | 4 % | |
| 0.75 - 1.00 | | 9 % | 6 % | 1 % | | |
| 1.00 - 1.25 | | 4 % | 1 % | | | |
| 1.25 - 1.50 | | 4 % | | | | |

*Table 3 Wave orbital velocities at various depths over the Baltic Proper banks.*

# 10 Appendices

## Fladen Bank

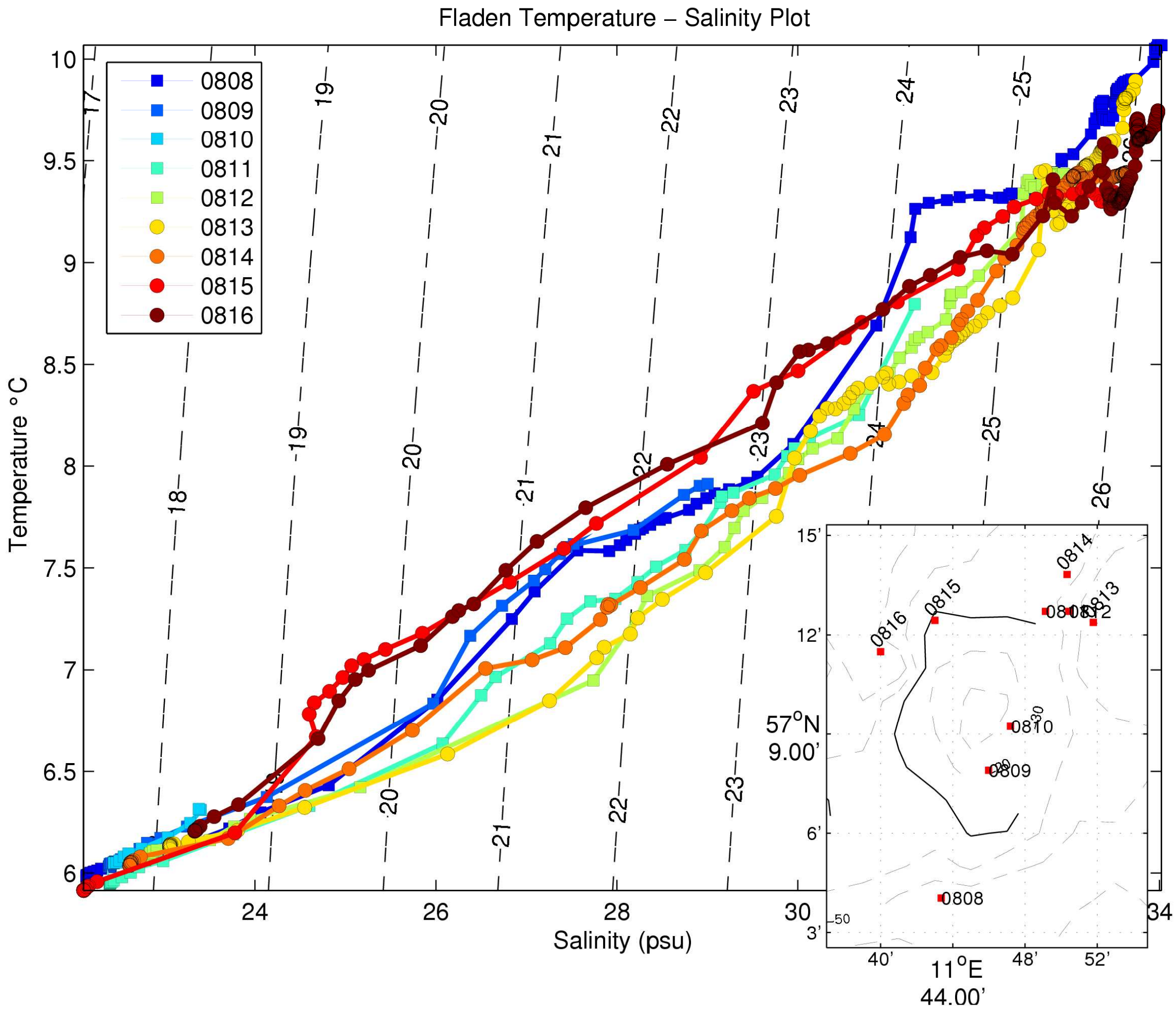


*Figure 15 Temperature salinity plot for Fladen*

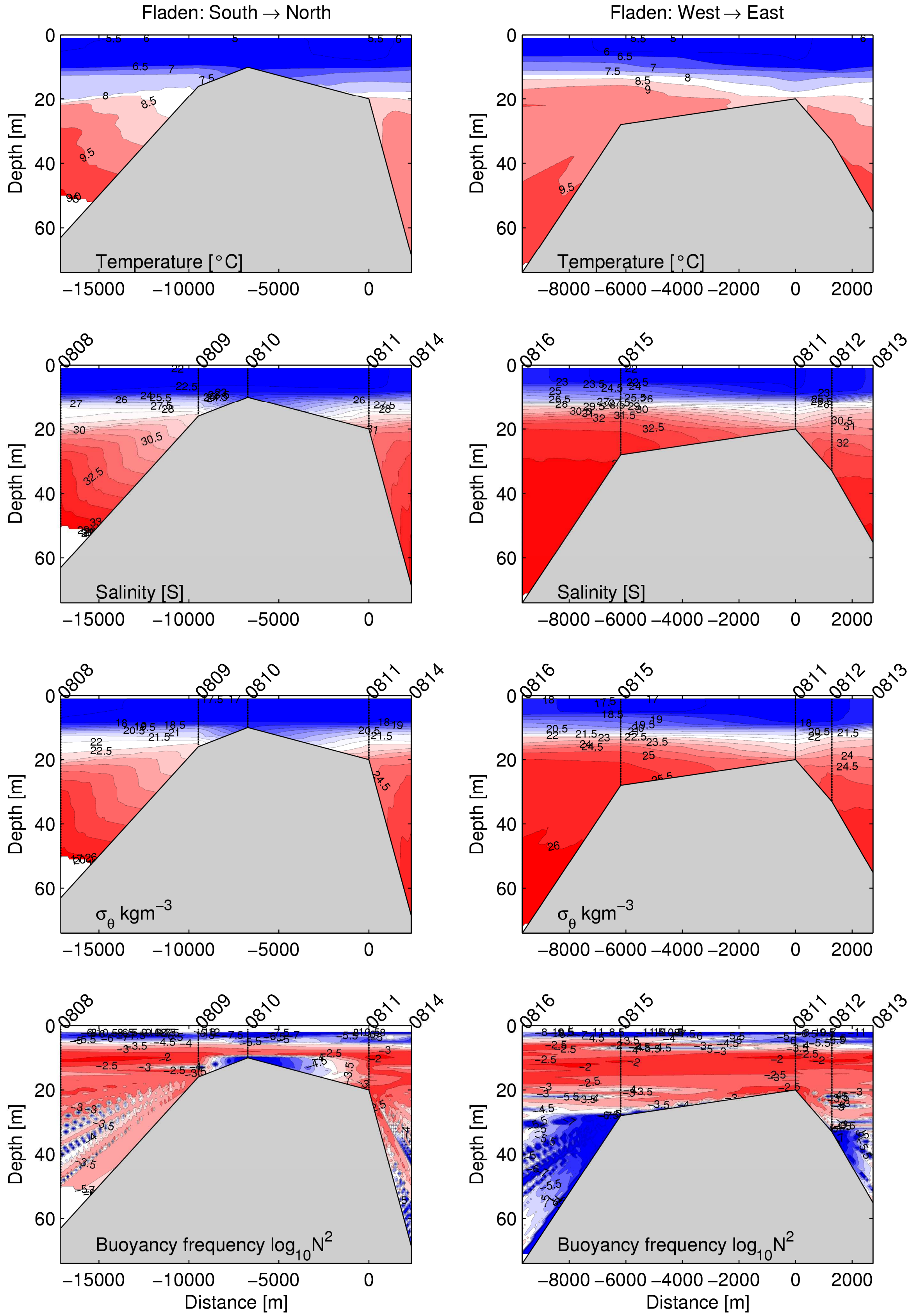


*Figure 16 Gridded hydrographic properties over Fladen*

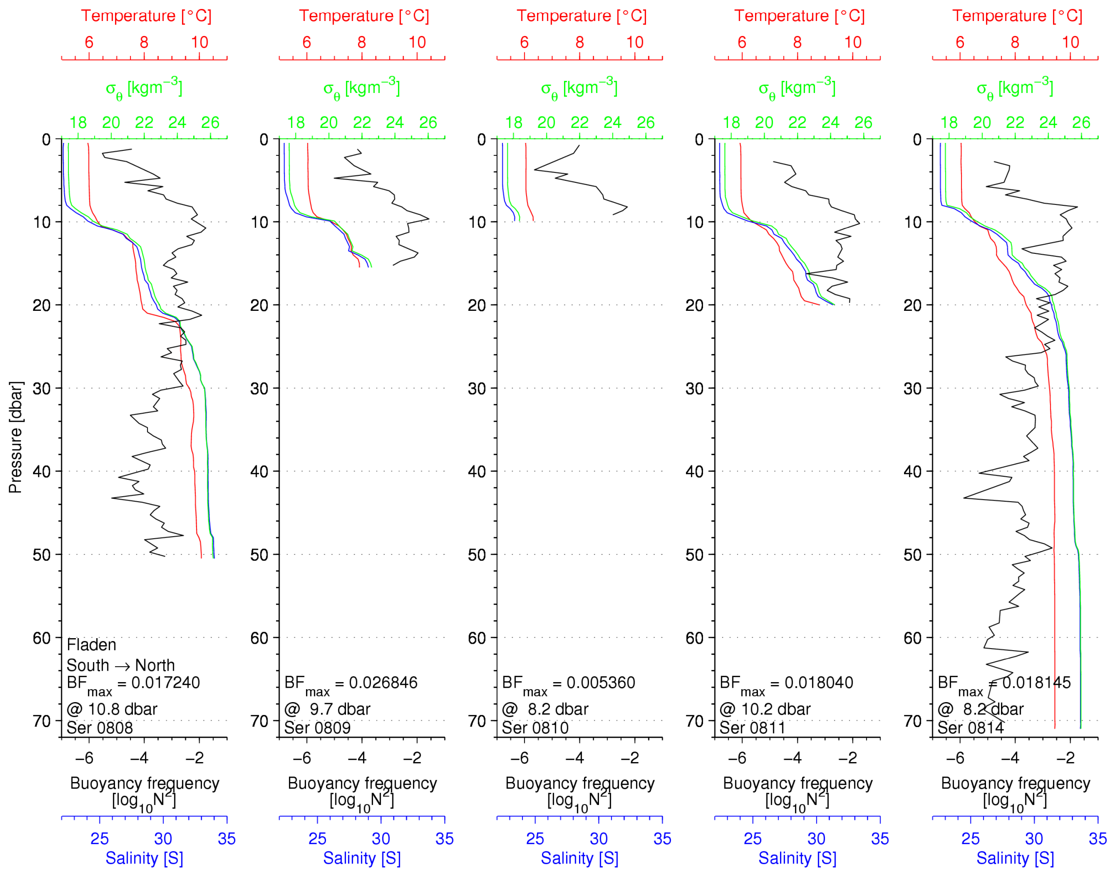


*Figure 17 CTD profiles from the south – north transect across Fladen*

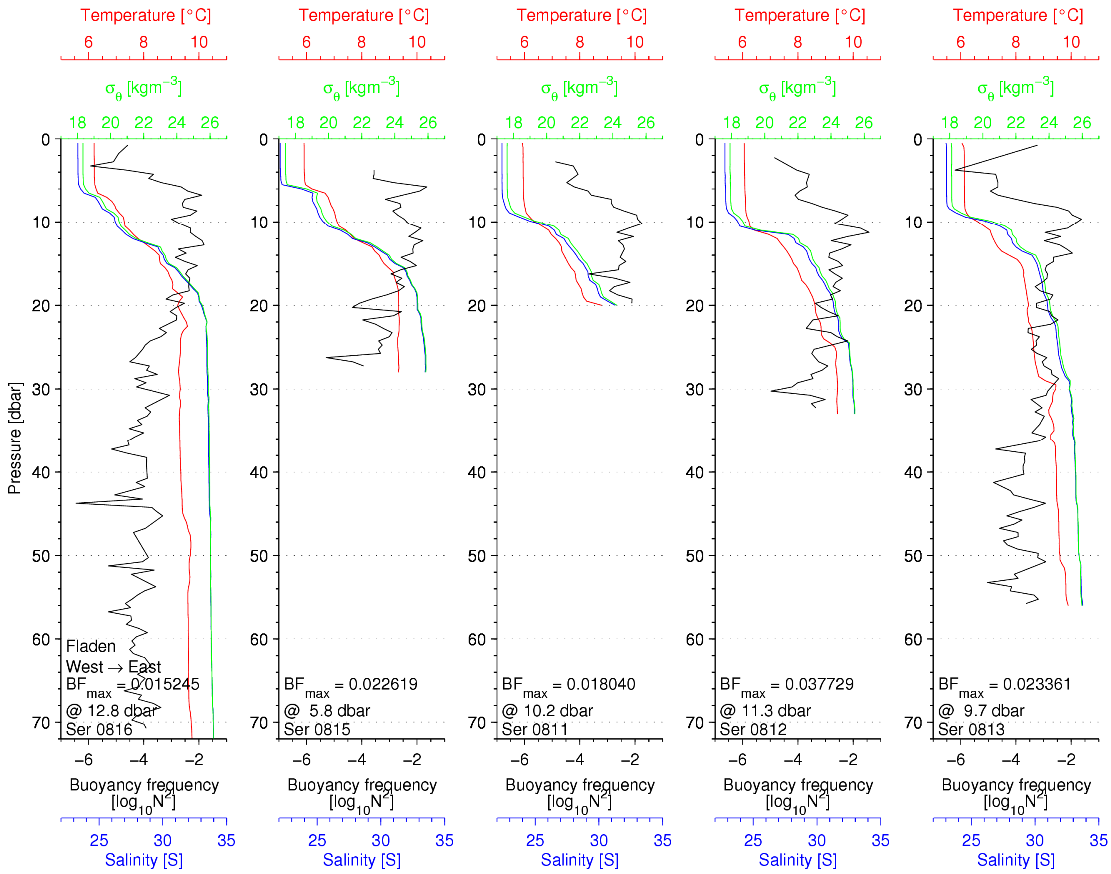


*Figure 18 CTD profiles from the west – east transect across Fladen*

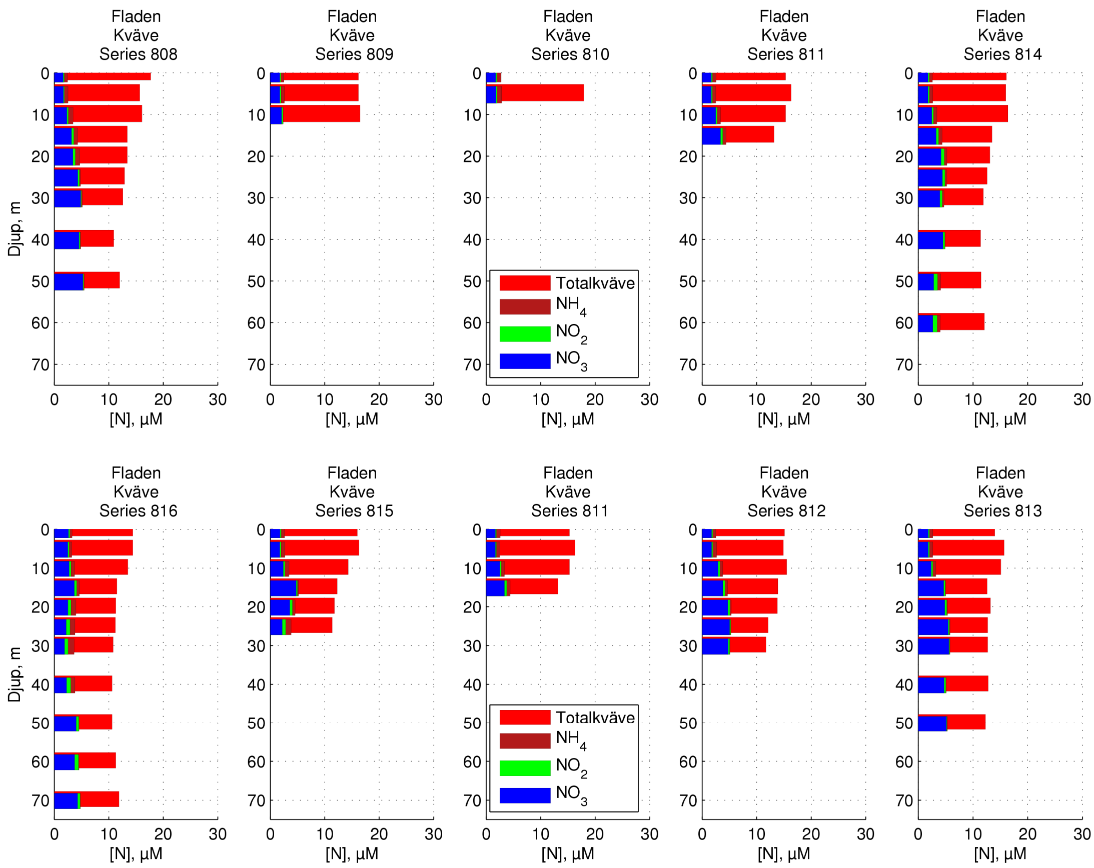


*Figure 19 Nitrogen concentrations across Fladen*

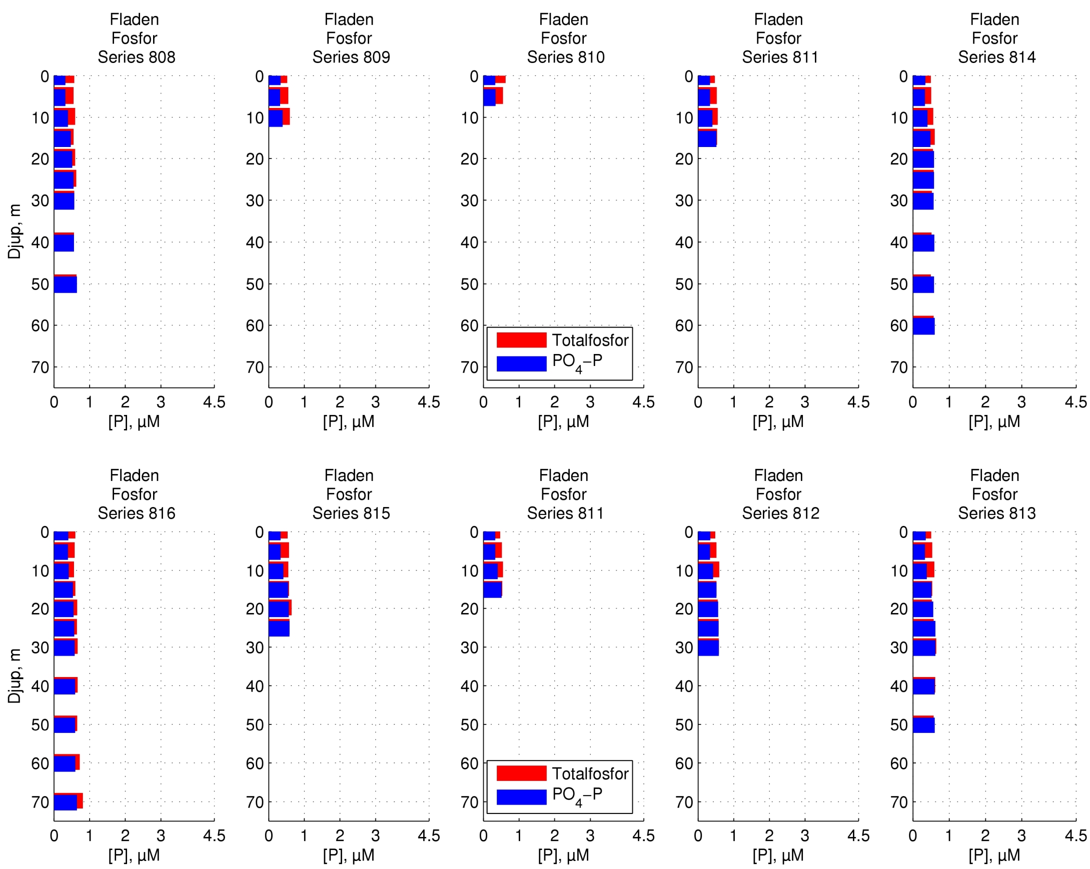


*Figure 20 Phosphorus concentrations across Fladen*

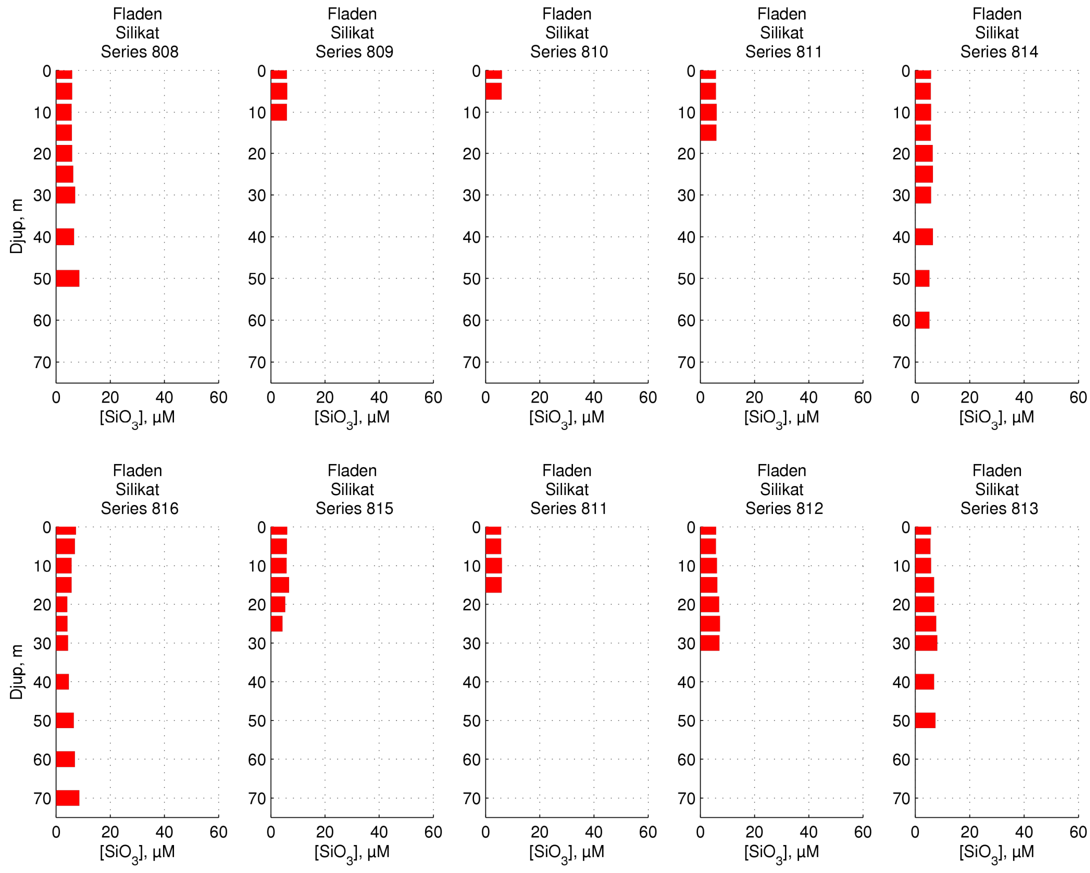


*Figure 21 Silicate concentrations across Fladen*

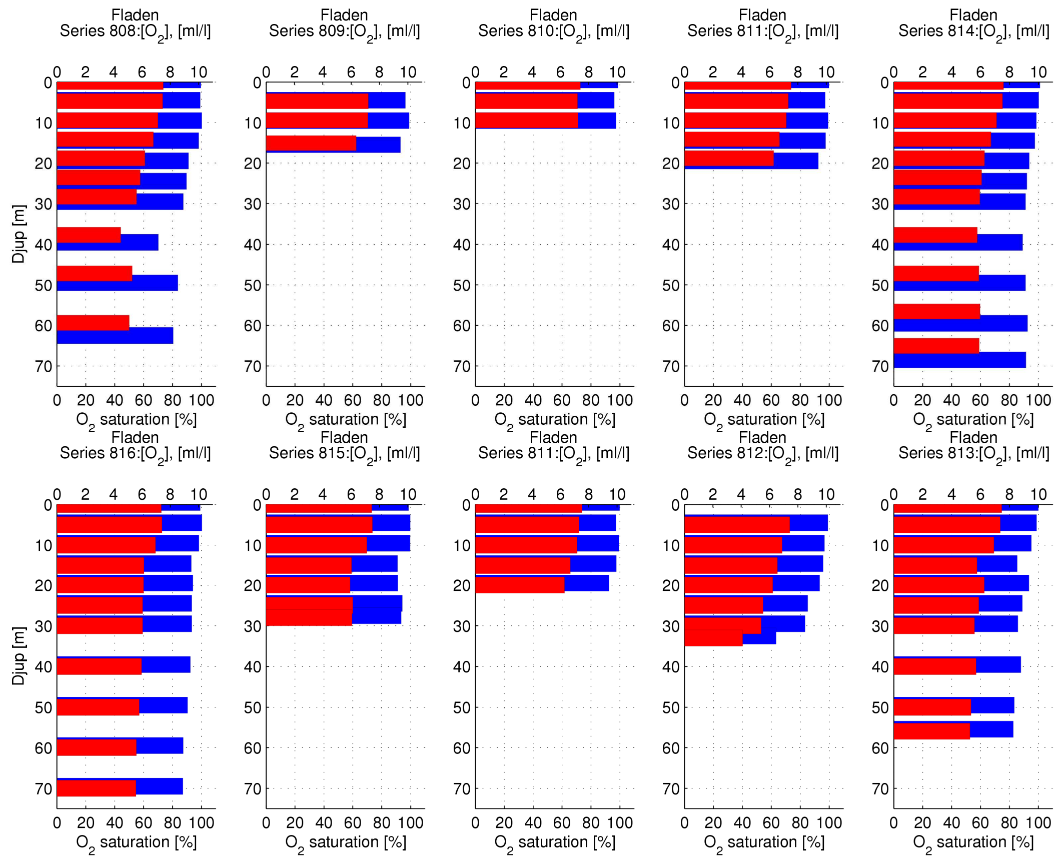


*Figure 22 Oxygen concentrations (red) and saturation (blue) across Fladen*

## Lilla Middelgrund

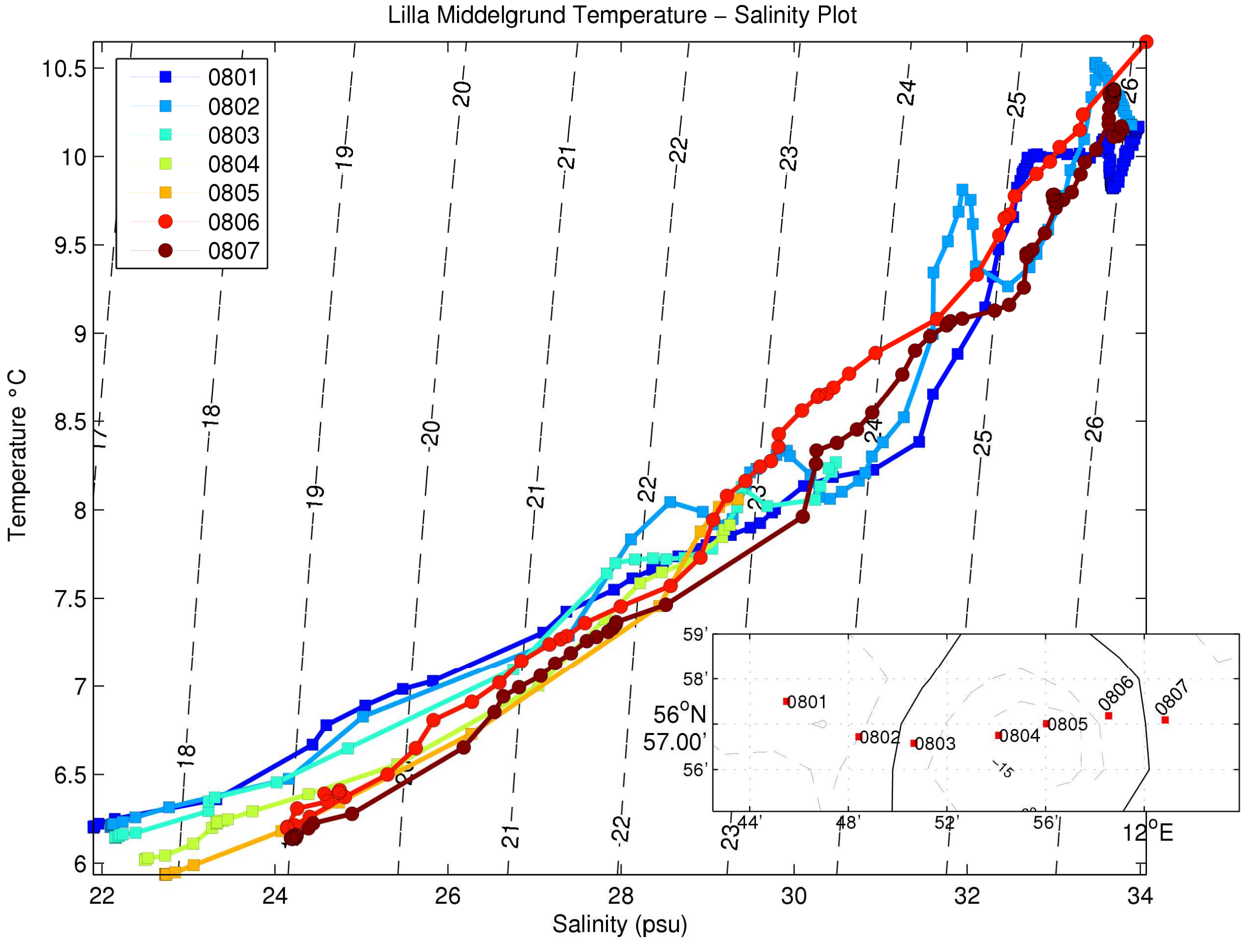


*Figure 23 Temperature - salinity plot over Lilla Middelgrund*

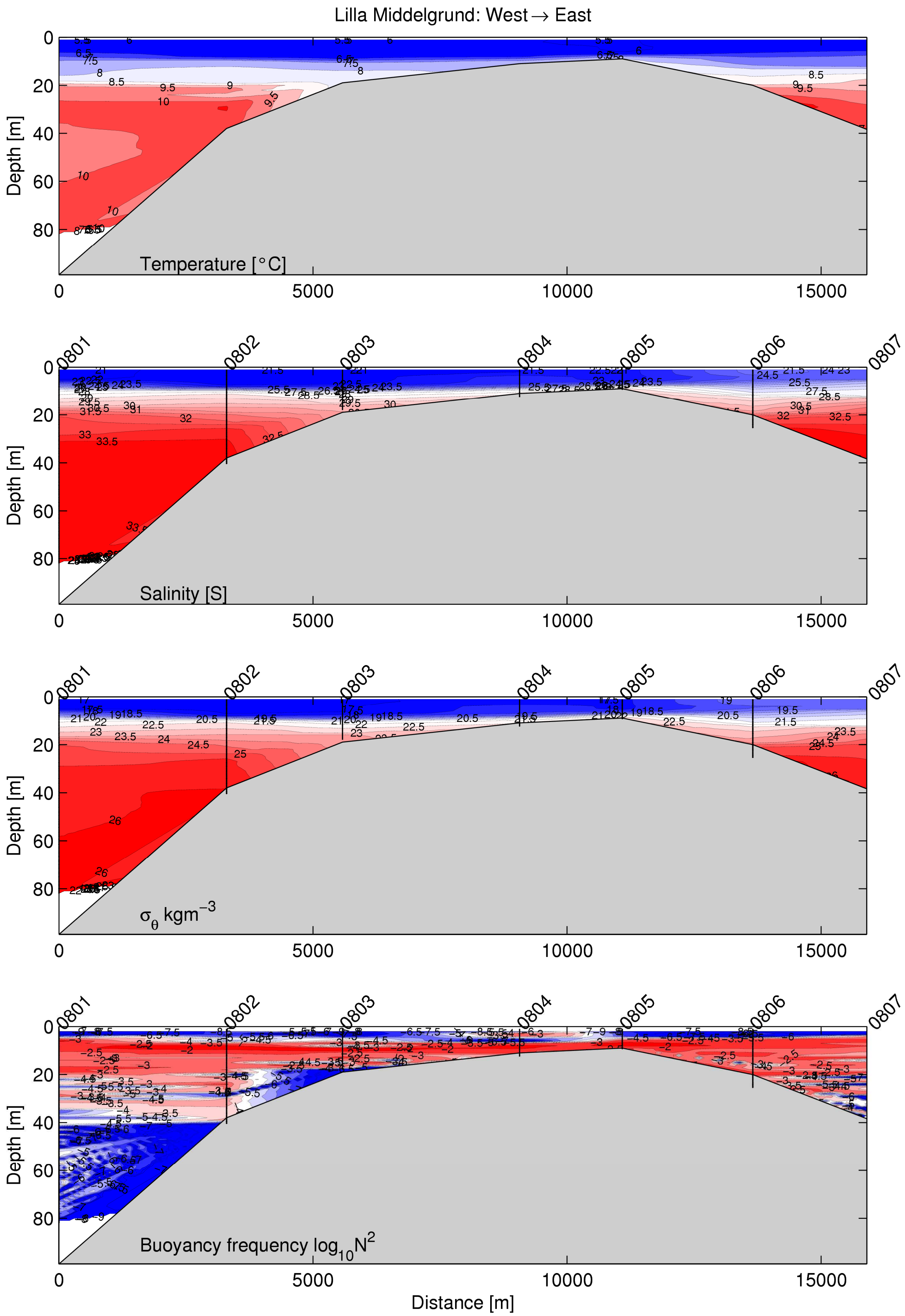


*Figure 24 Hydrographic variables gridded over Lilla Middelgrund*

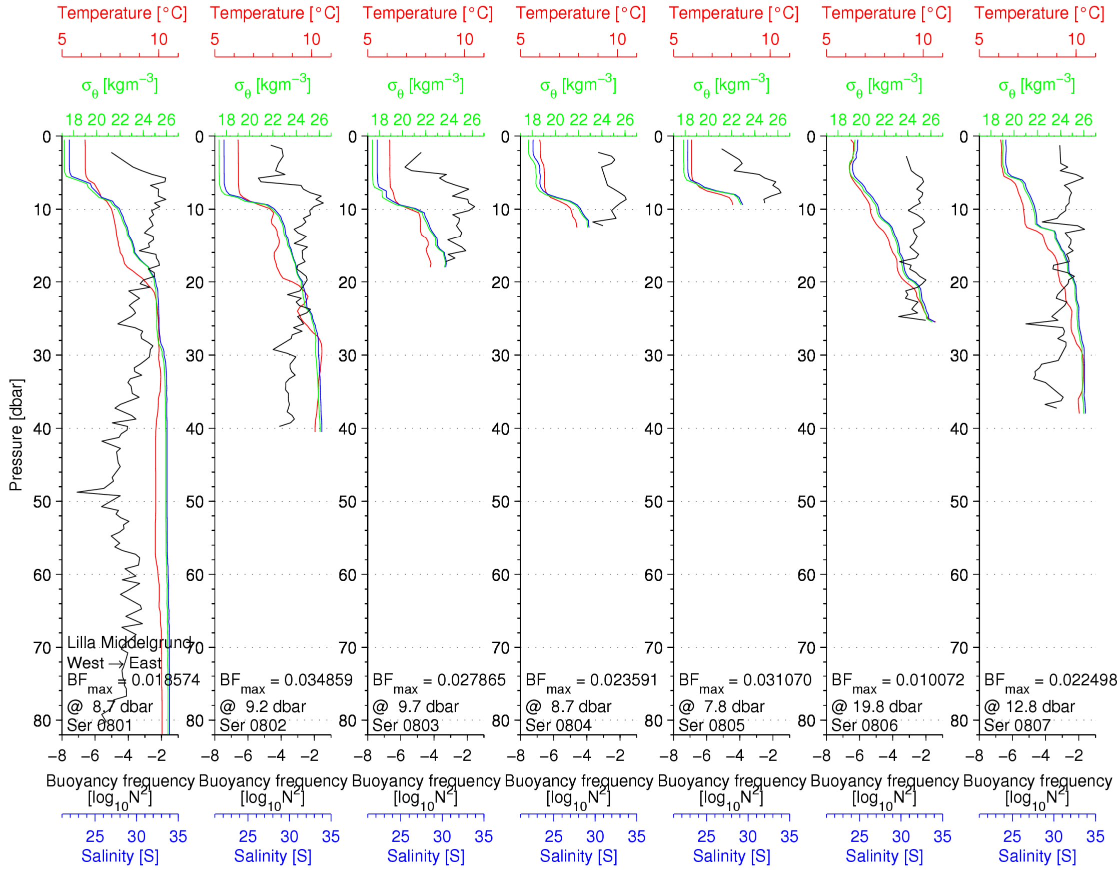


*Figure 25 Temperature, salinity and buoyancy frequency profiles across Lilla Middelgrund.*

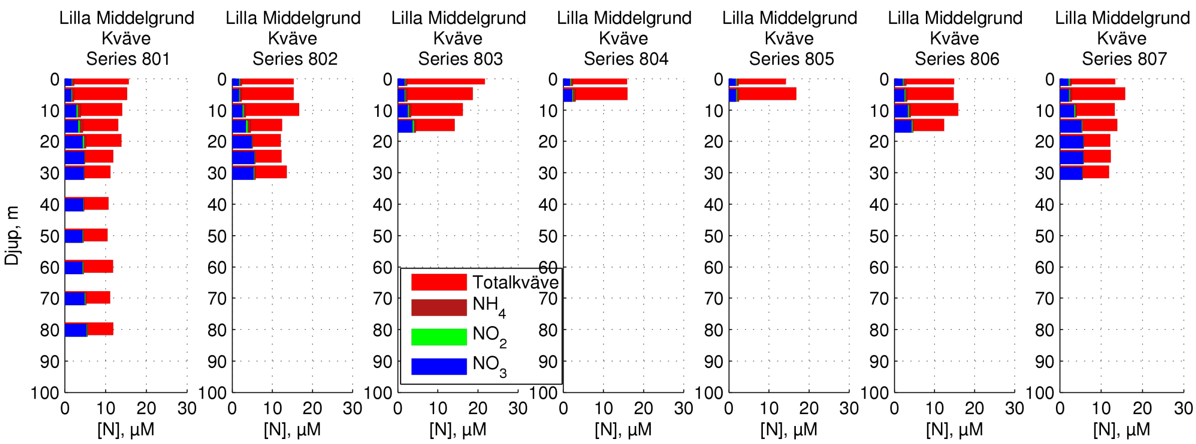


*Figure 26 Nitrogen concentrations across Lilla Middelgrund*

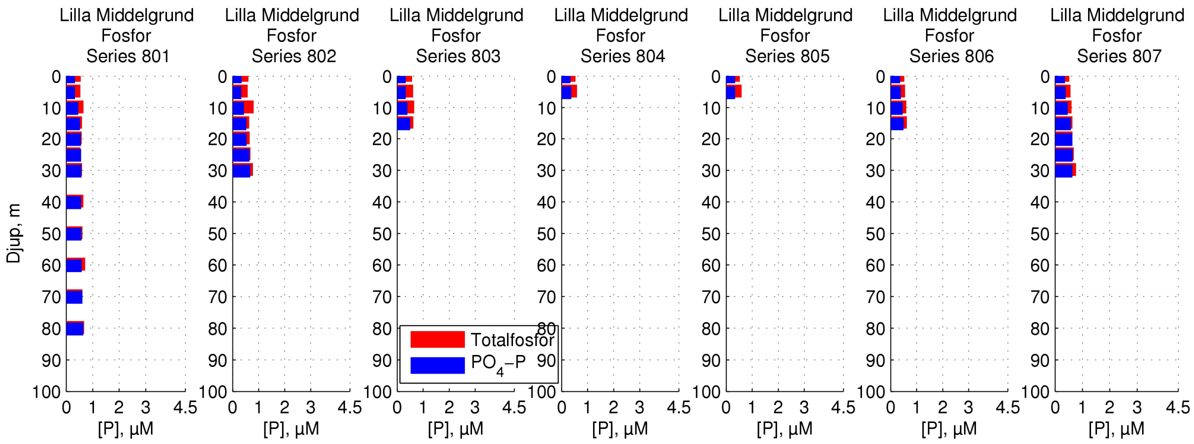


*Figure 27 Phosphorus concentrations across Lilla Middelgrund*

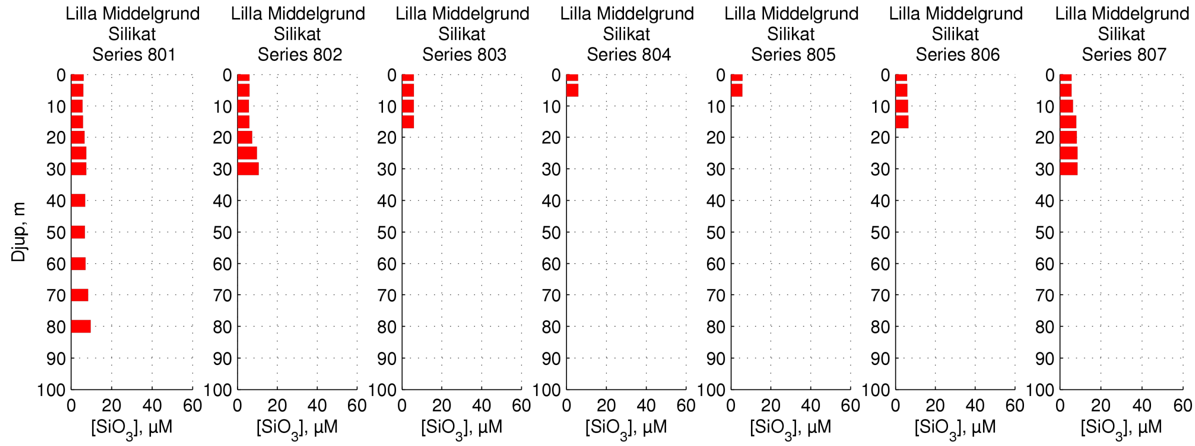


*Figure 28 Silicate concentrations across Lilla Middelgrund*

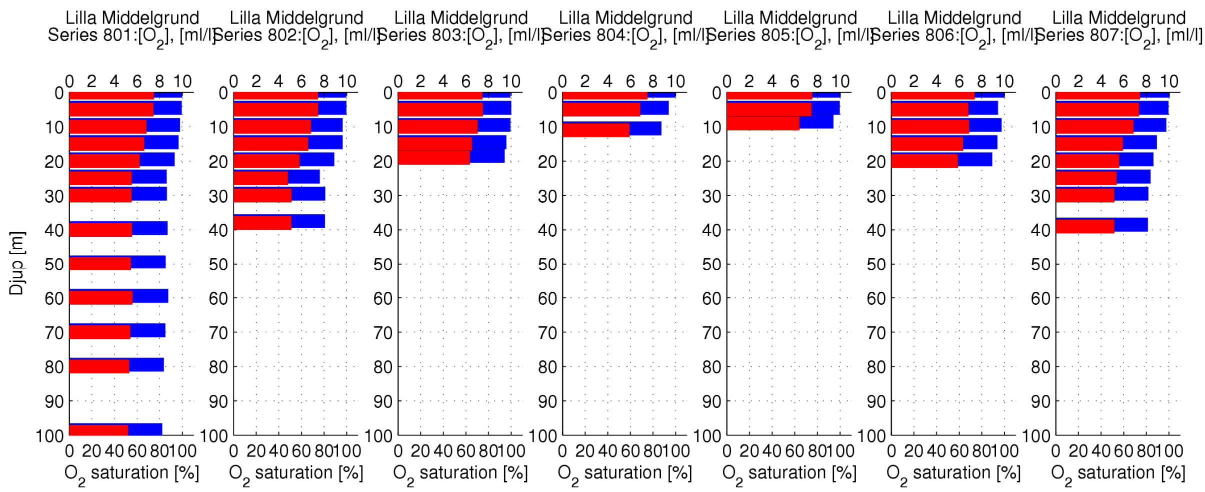


*Figure 29 Oxygen concentrations (red) and saturation (blue) across Lilla Middelgrund*

## Röde Bank

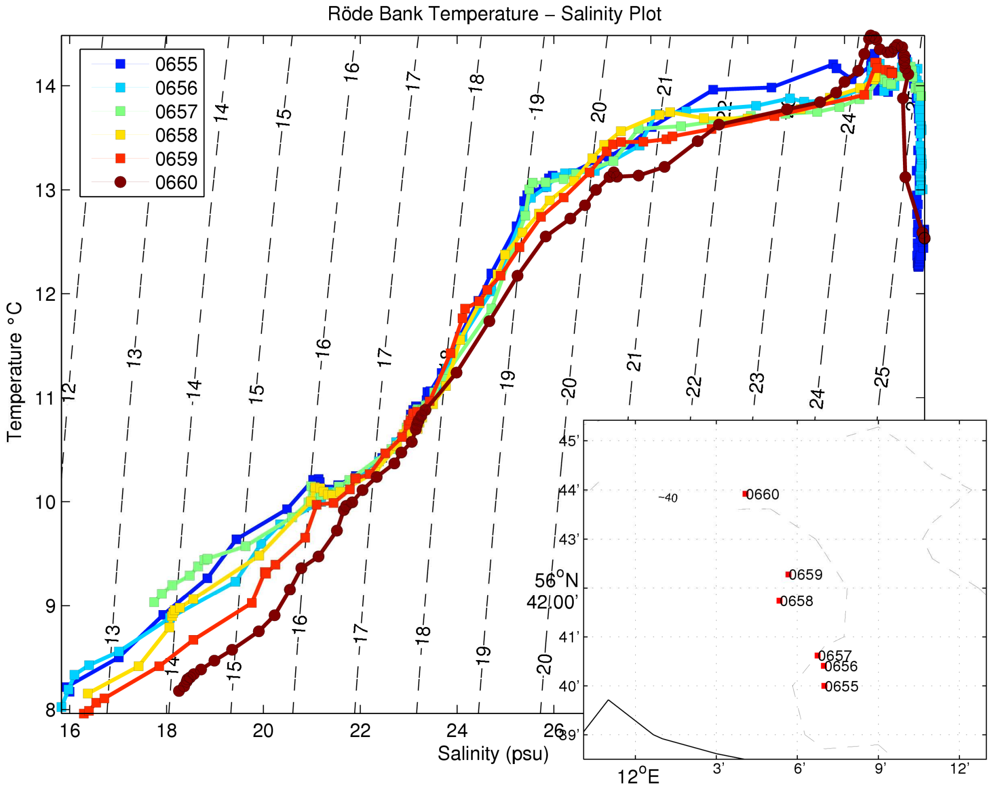


*Figure 30 Temperature – Salinity plot over Röde Bank*

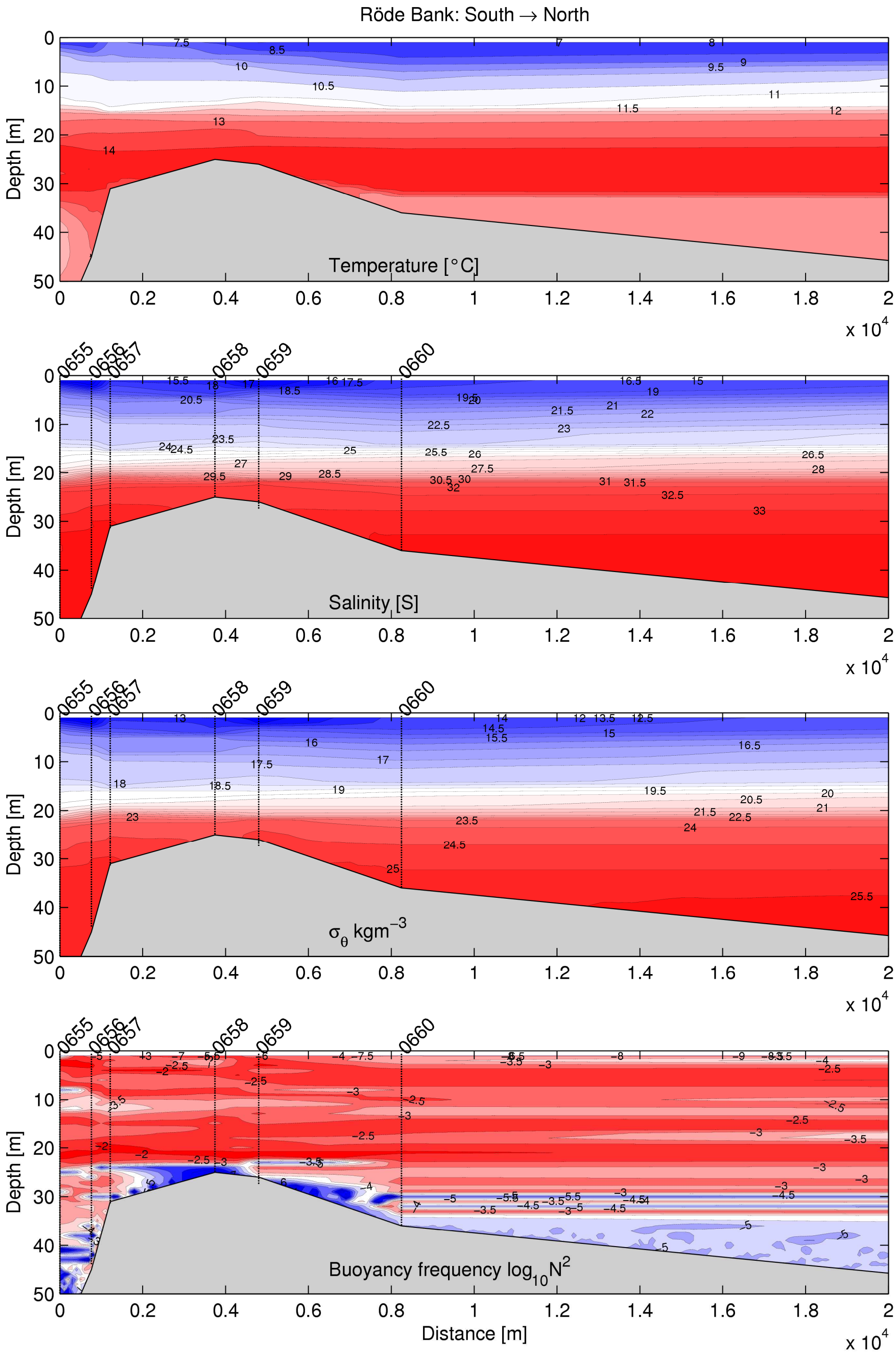


*Figure 31 Hydrography over Röde Bank, gridded from south to north.*

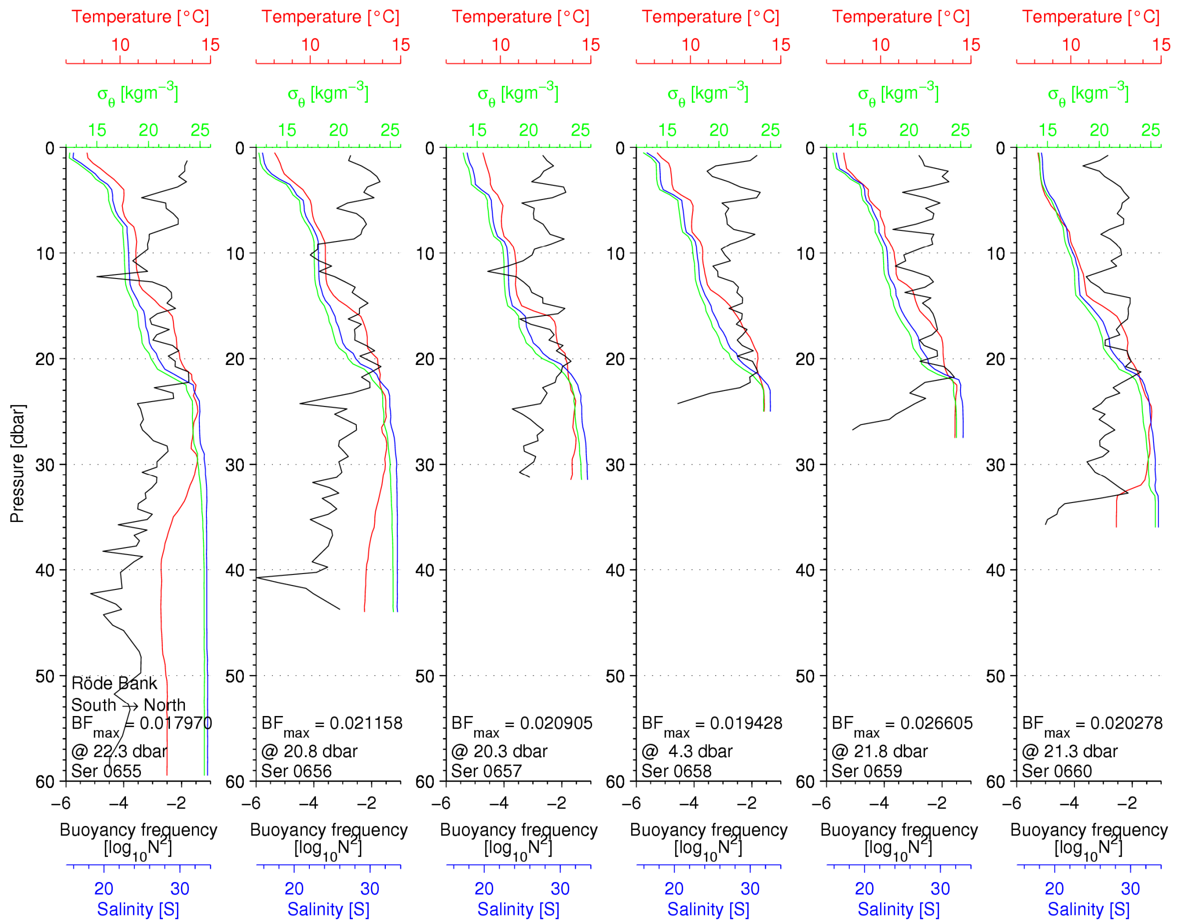


*Figure 32 CTD profiles measured over Röde Bank*

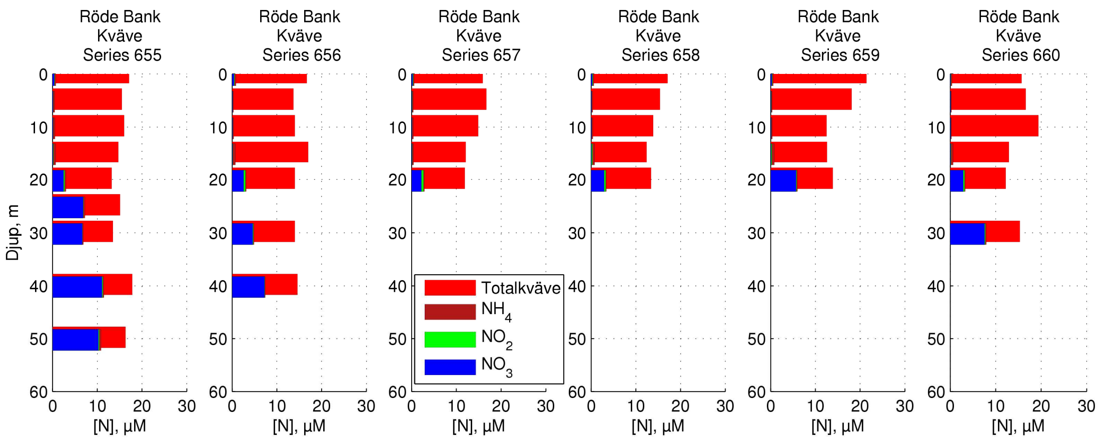


*Figure 33 Nitrogen concentrations acrossRöde Bank*

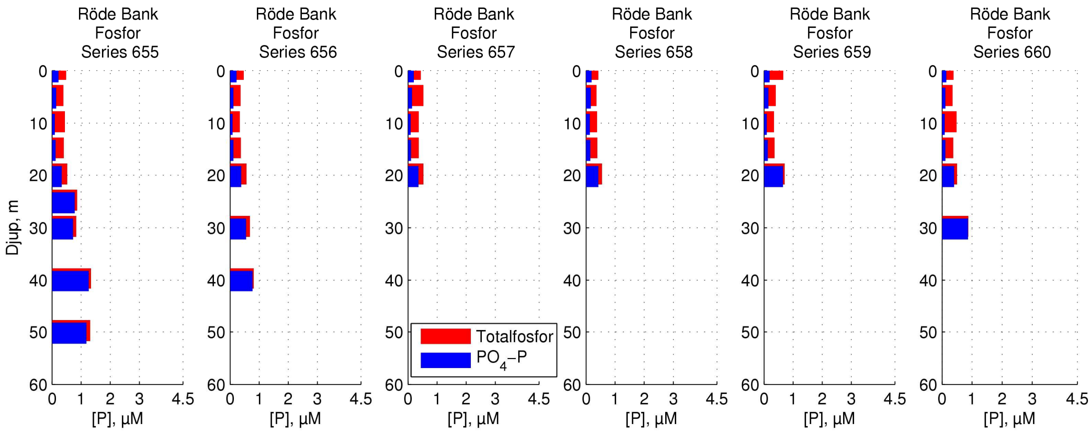


*Figure 34 Phosphorus concentrations across Röde Bank*

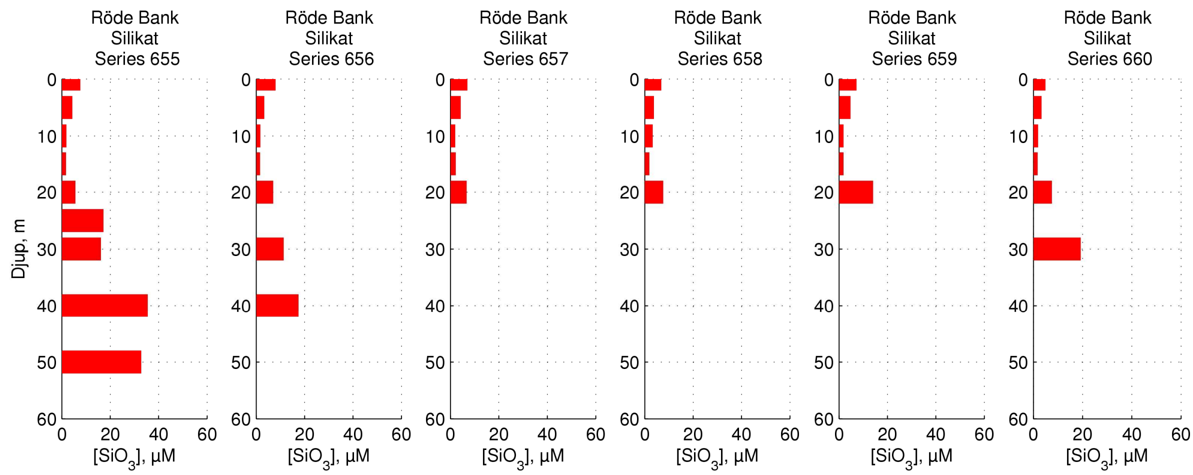


*Figure 35 Röde Bank silicate concentrations*

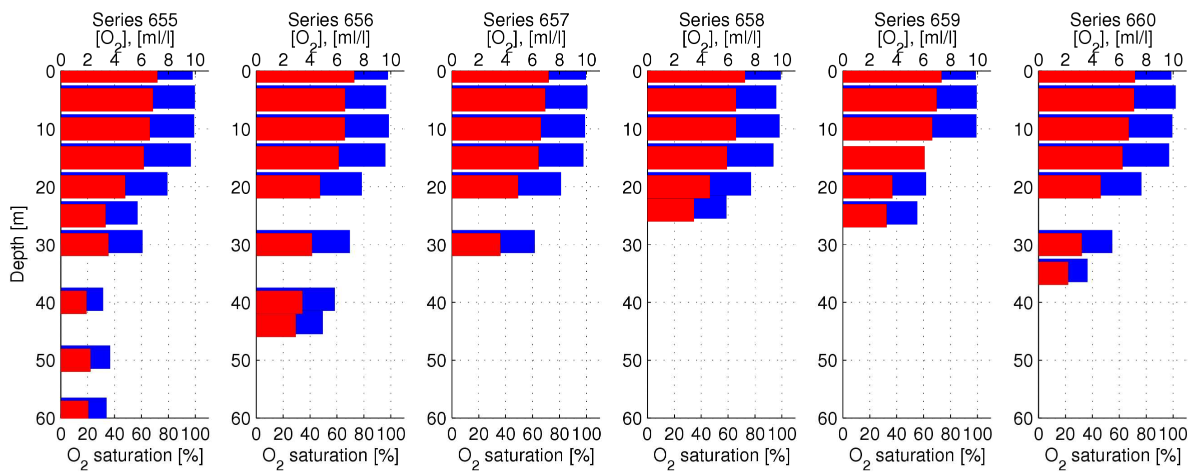


*Figure 36 Röde Bank oxygen concentration (red) and saturation(blue)*

## Stora Middelgrund

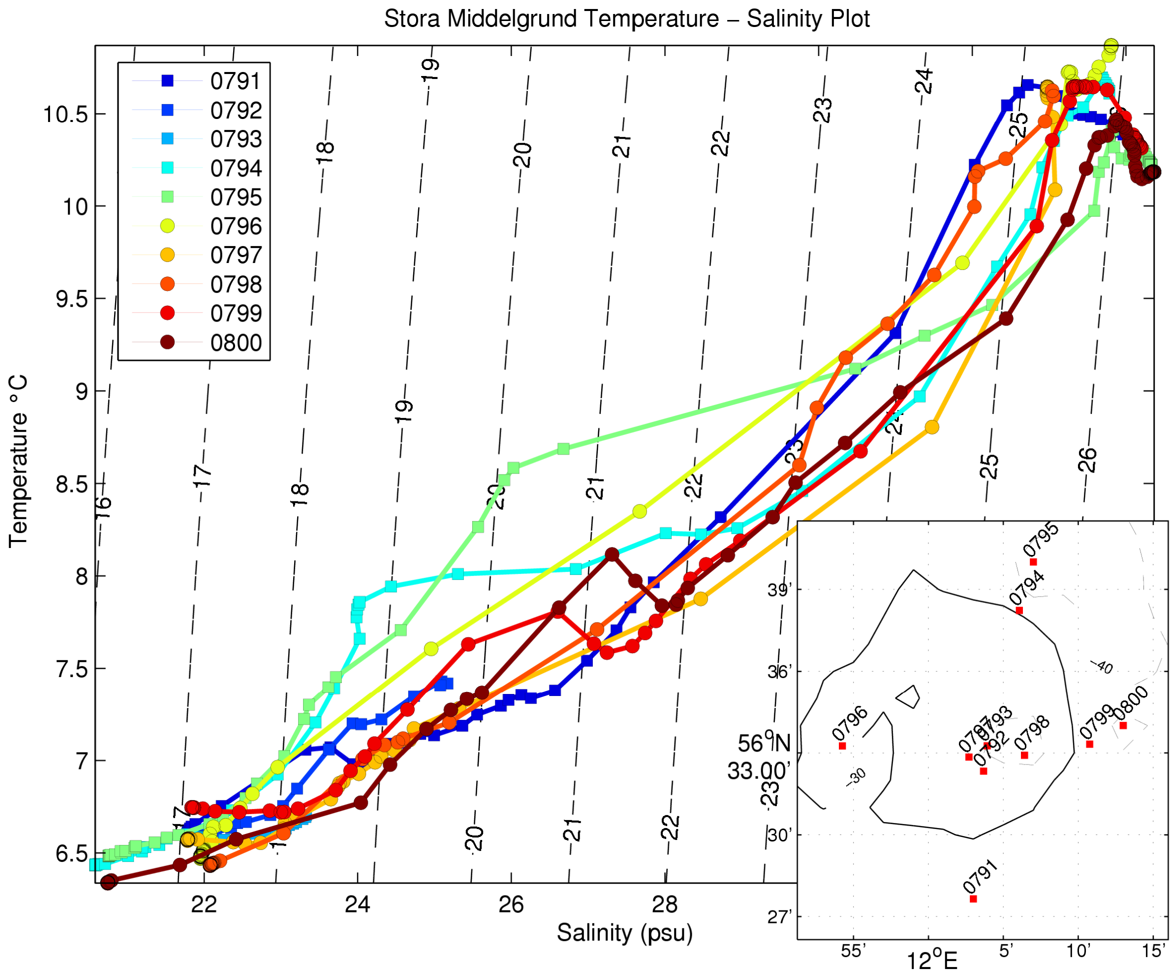


*Figure 37 Stora Middelgrund Temperature – salinity plot*

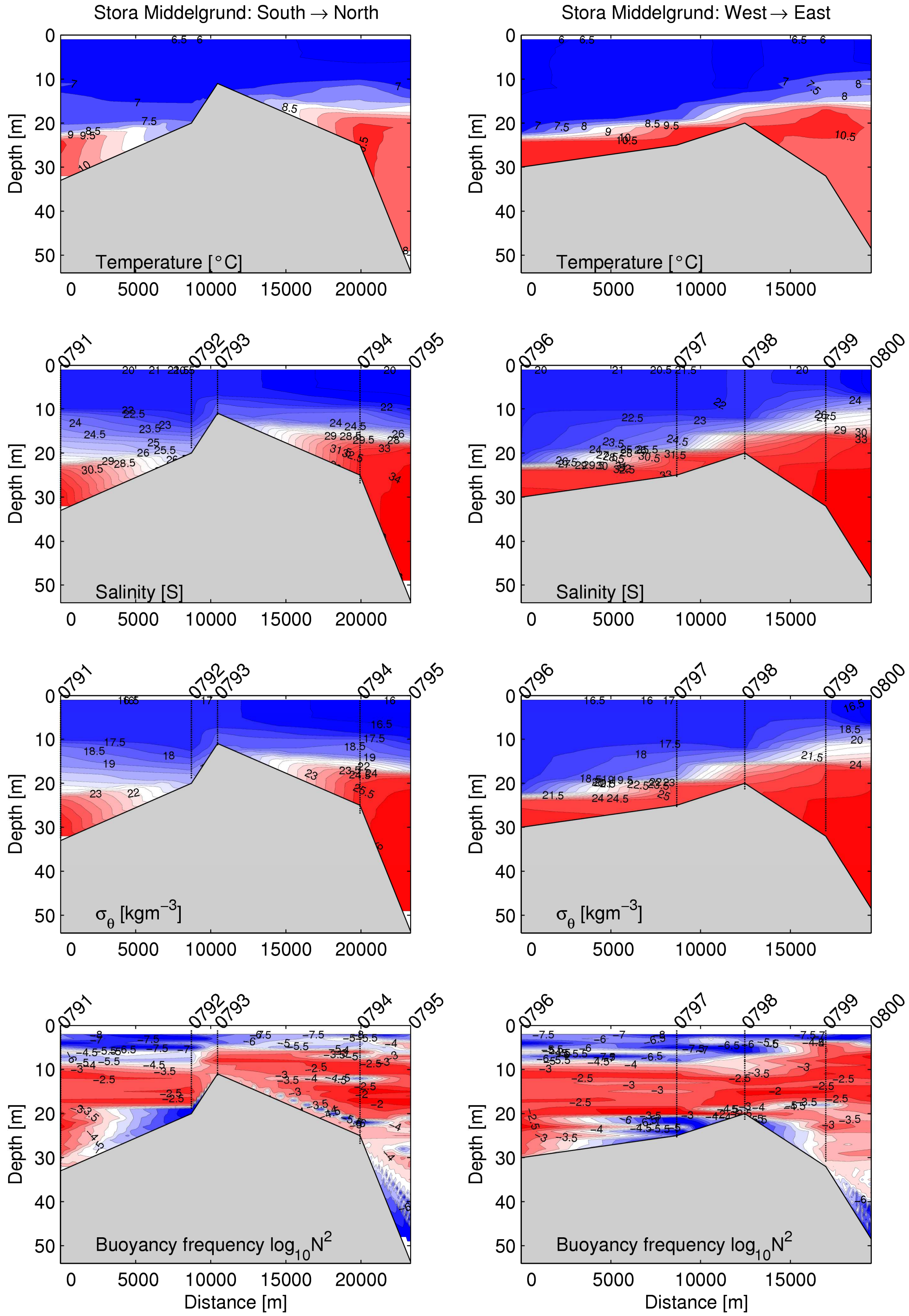


*Figure 38 Gridded hydrographic parameters across Stora Middelgrund*

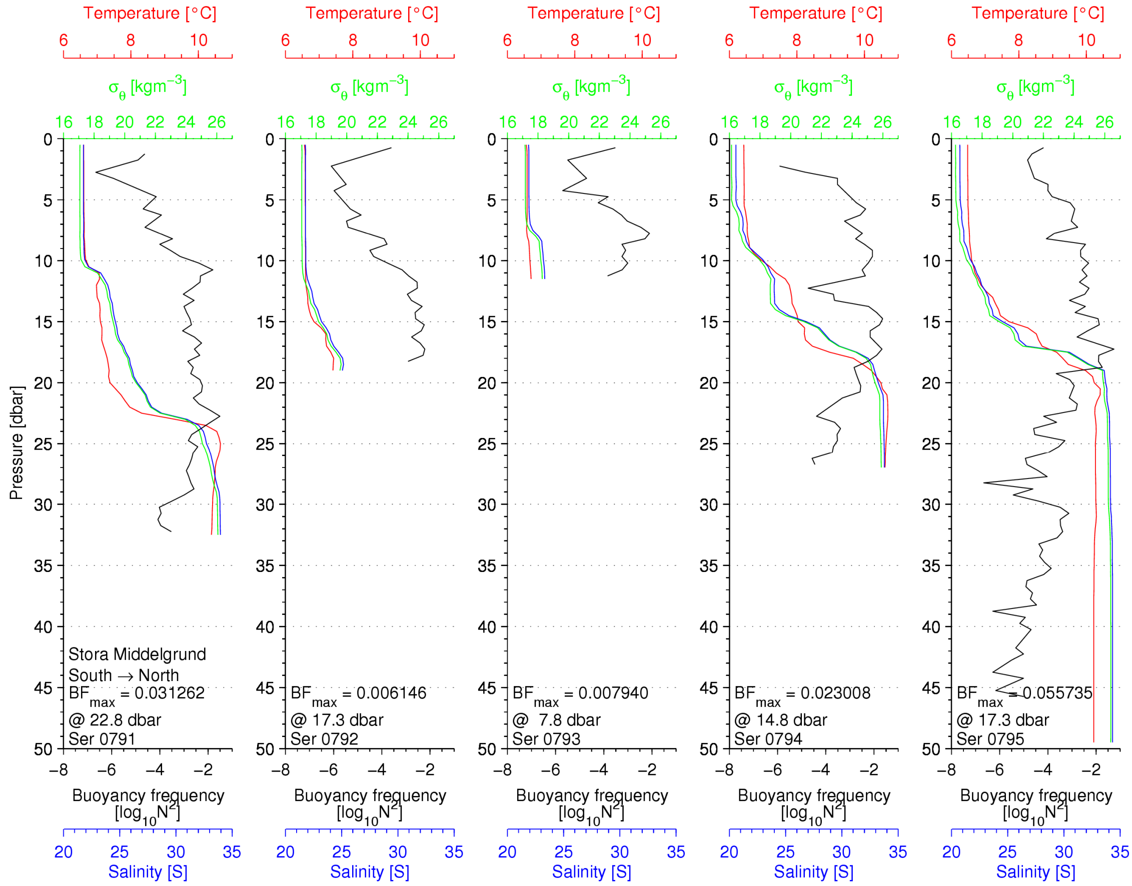


*Figure 39 CTD profiles across Stora Middelgrund from south to north*

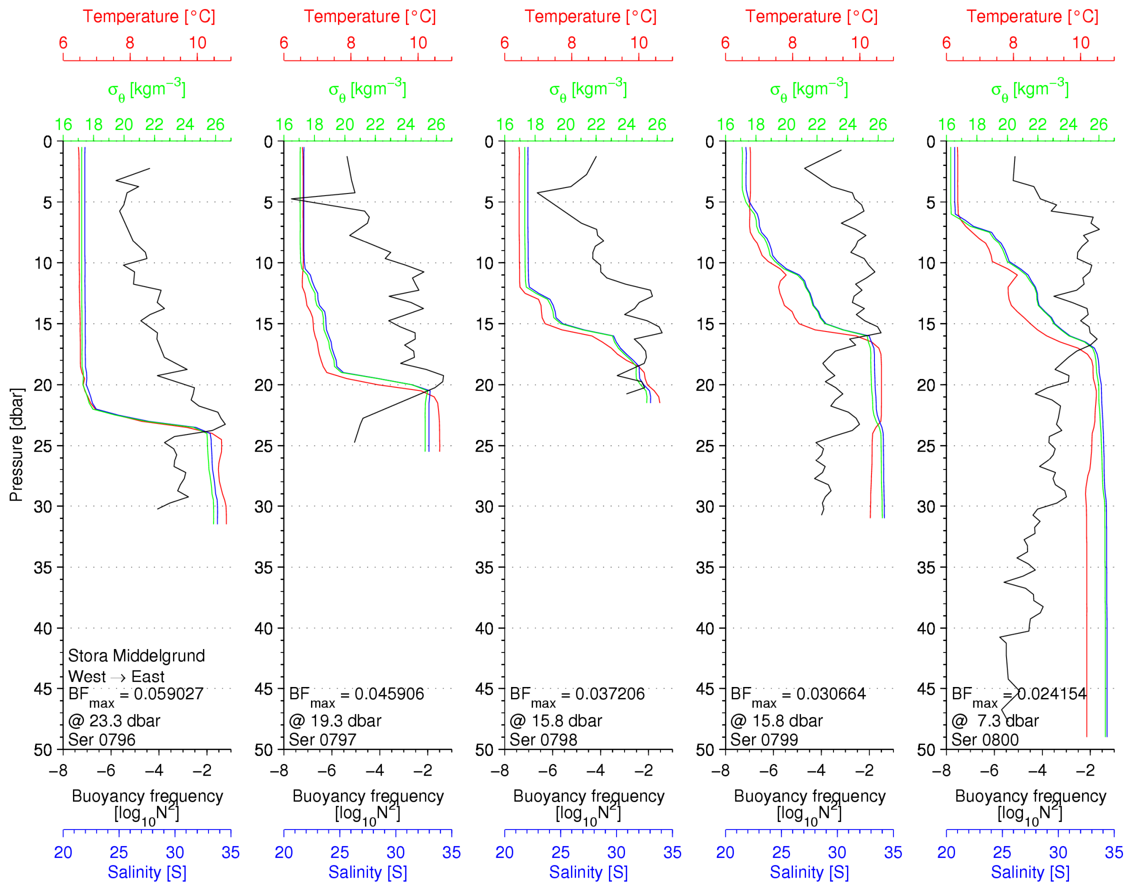


*Figure 40 CTD profiles across Stora Middelgrund from west to east*

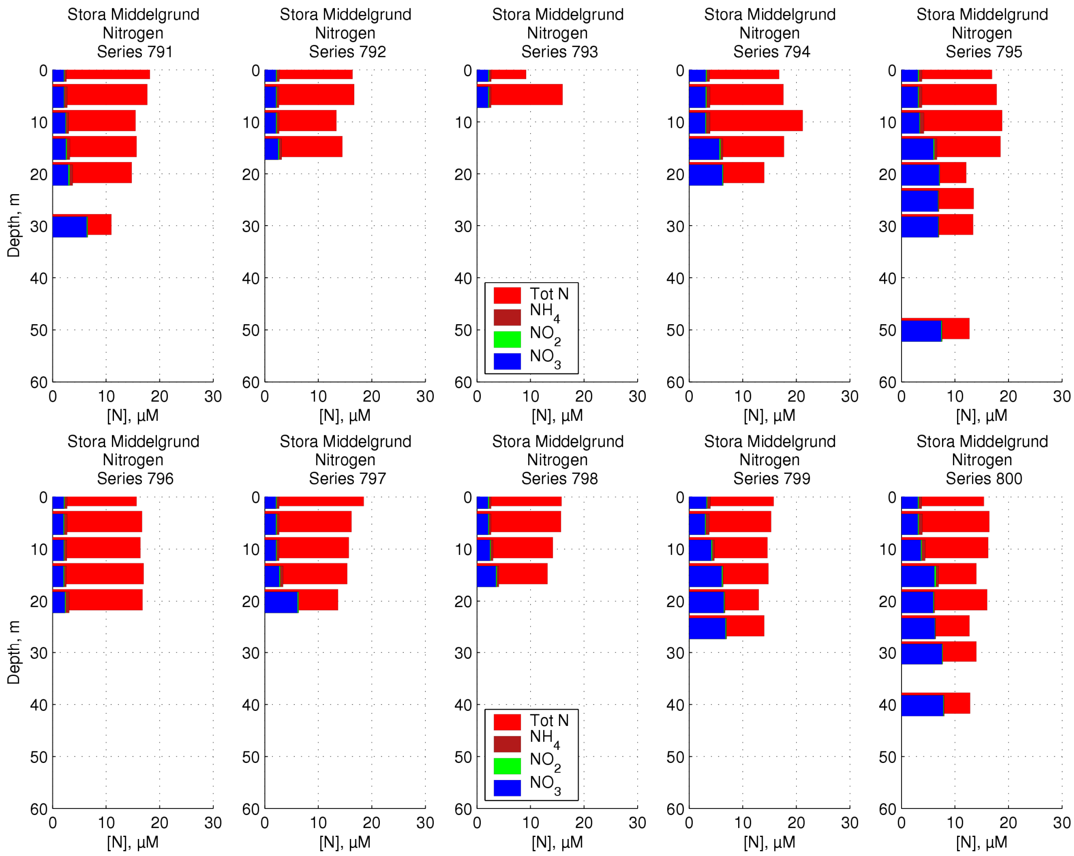


*Figure 41 Stora Middelgrund nitrogen concentrations*

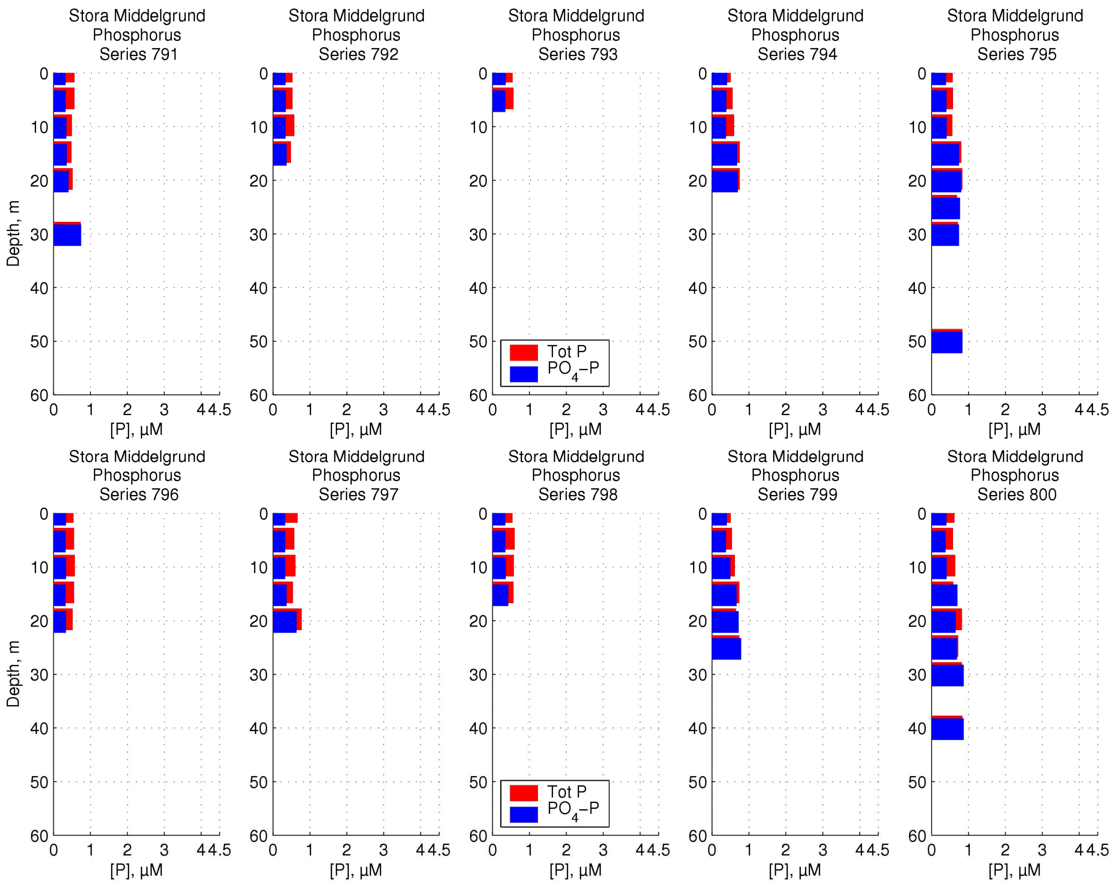


*Figure 42 Stora Middelgrund phosphorus concentrations*

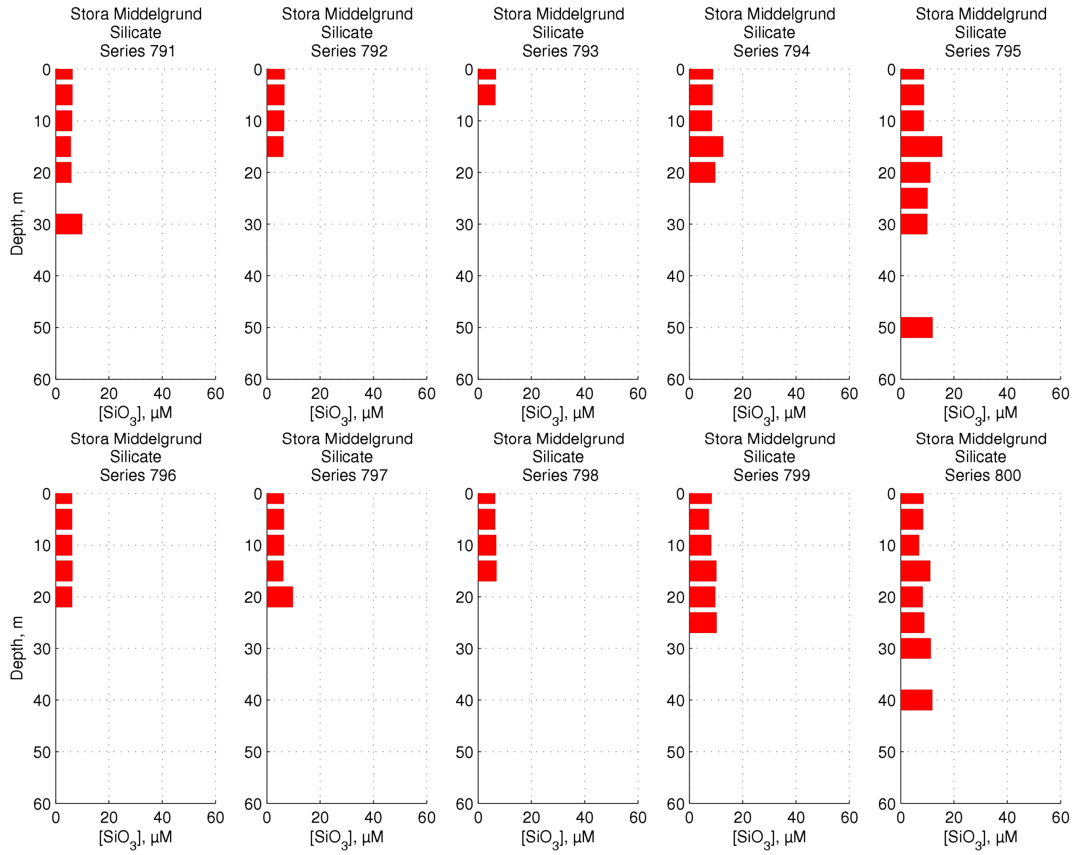


*Figure 43 Stora Middelgrund silicate concentrations*

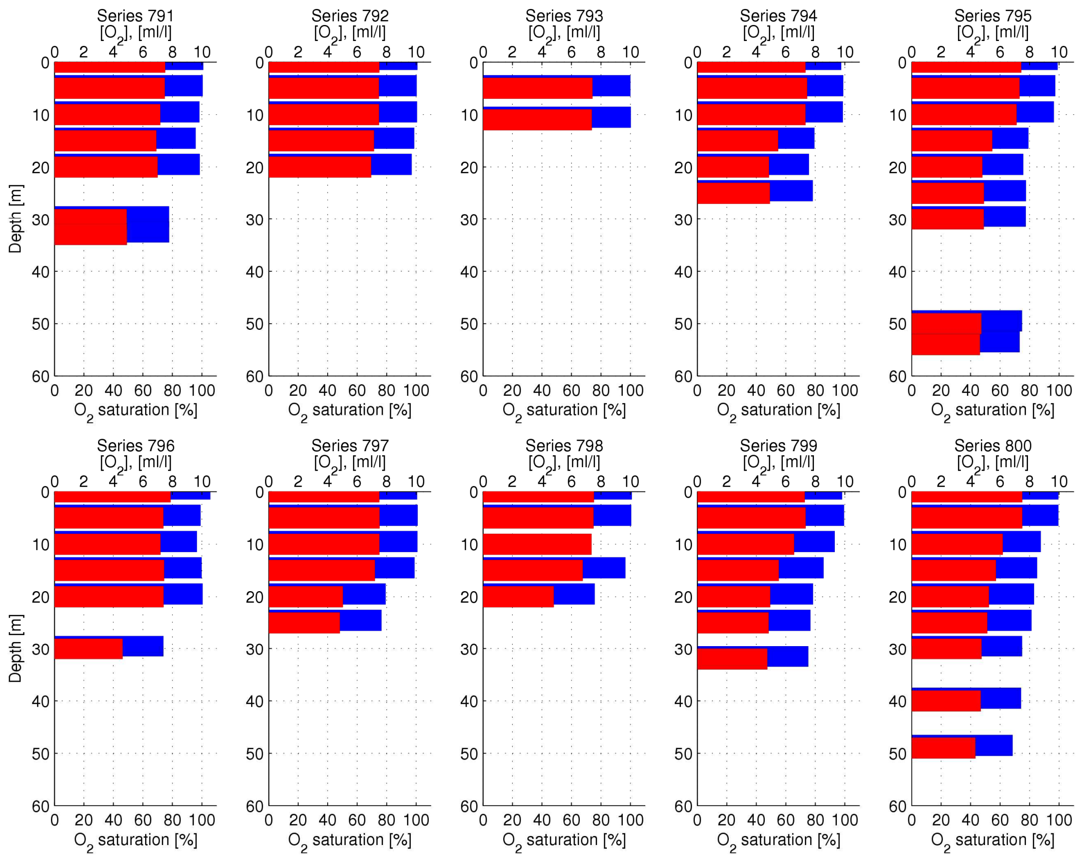


*Figure 44 Stora Middelgrund oxygen concentration (red) and saturation (blue)*

# Kriegers Flak

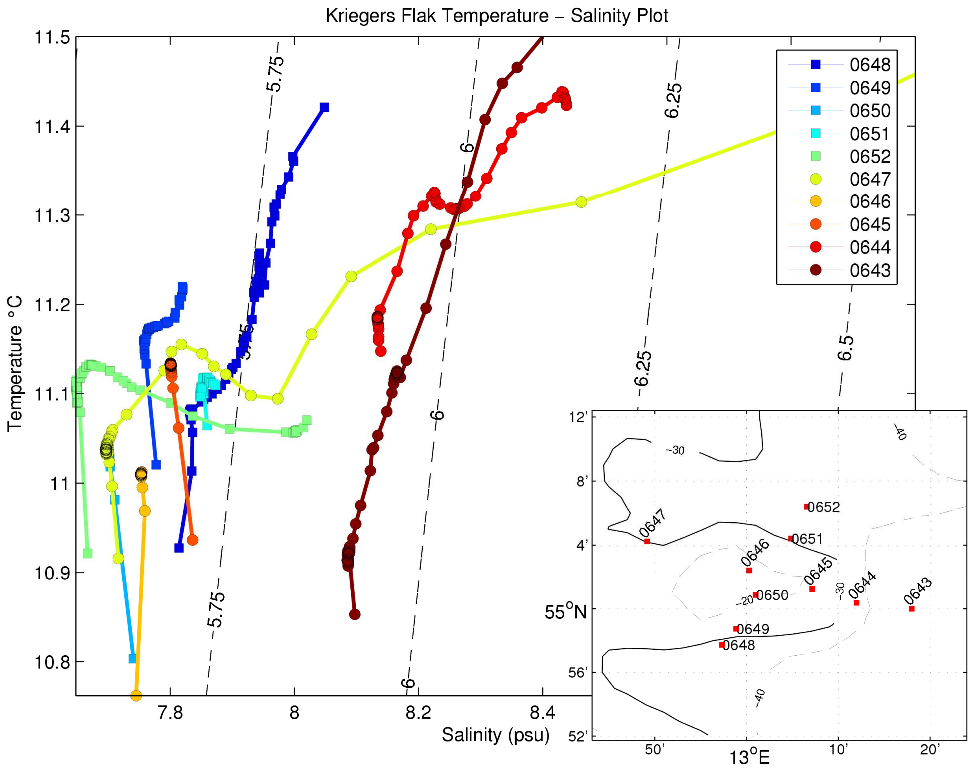


*Figure 45 Kriegers Flak (enlarged) temperature and salinity plot*

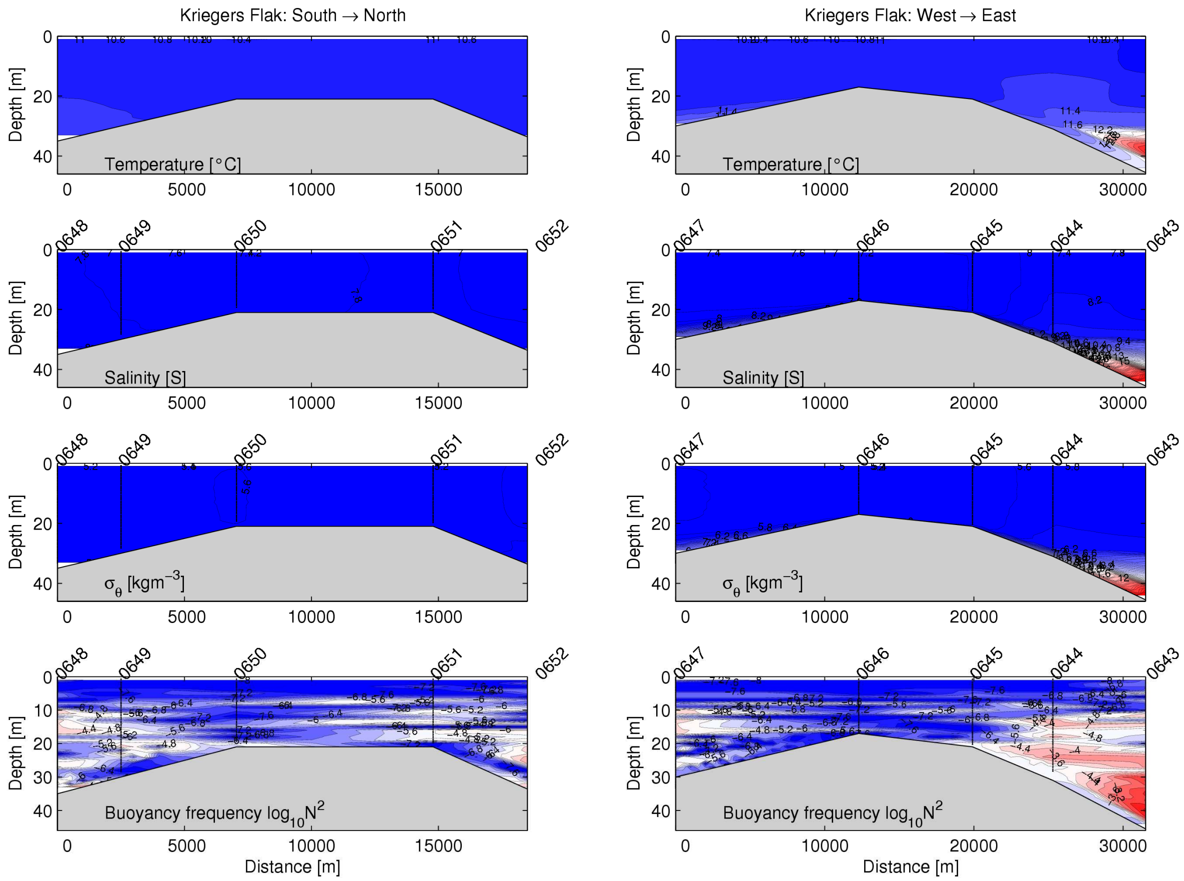


*Figure 46 Hydrographic parameters gridded across Kriegers Flak*

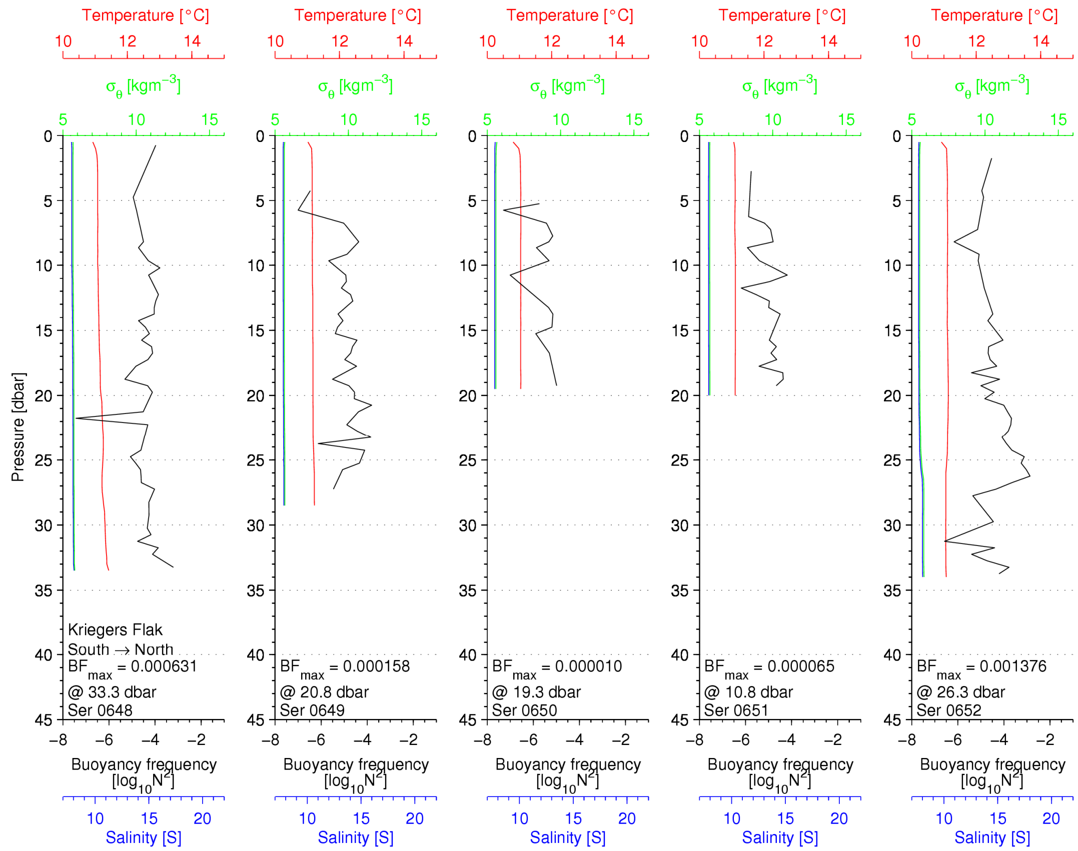


*Figure 47 CTD profiles along the south – north transect over Kriegers Flak*

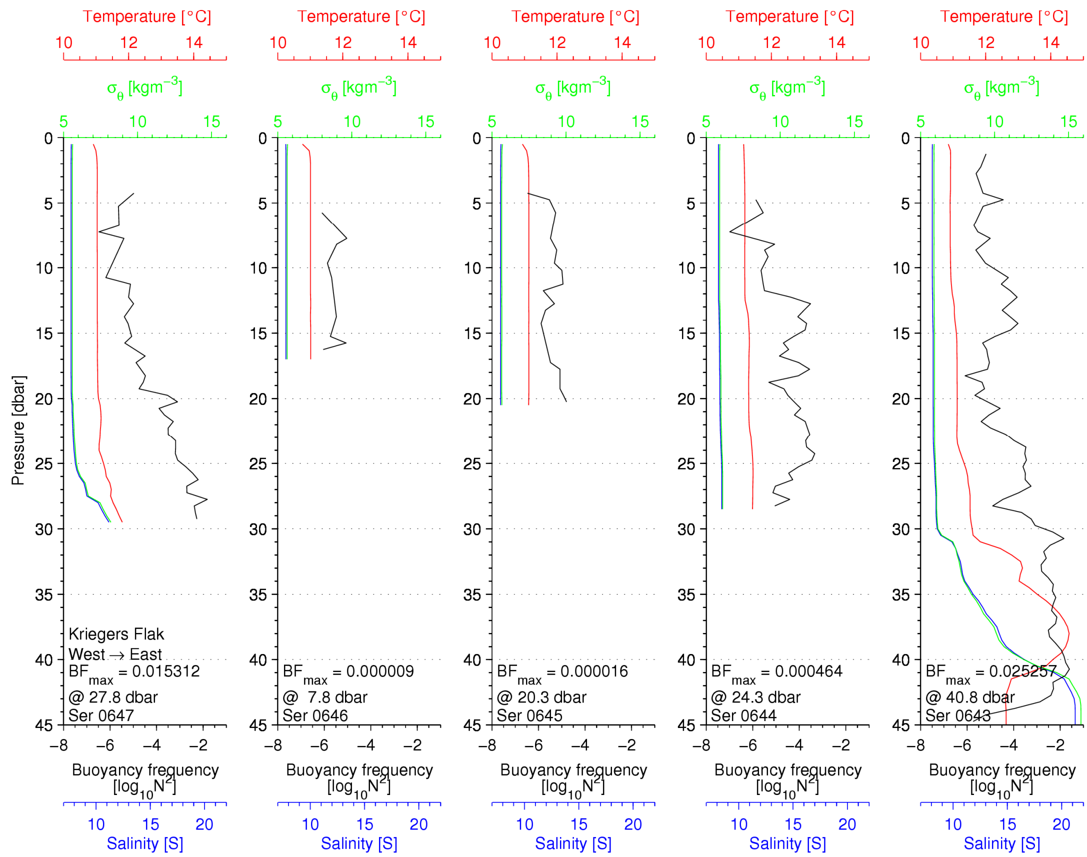


*Figure 48 CTD profiles along the west – east transect over Kriegers Flak*

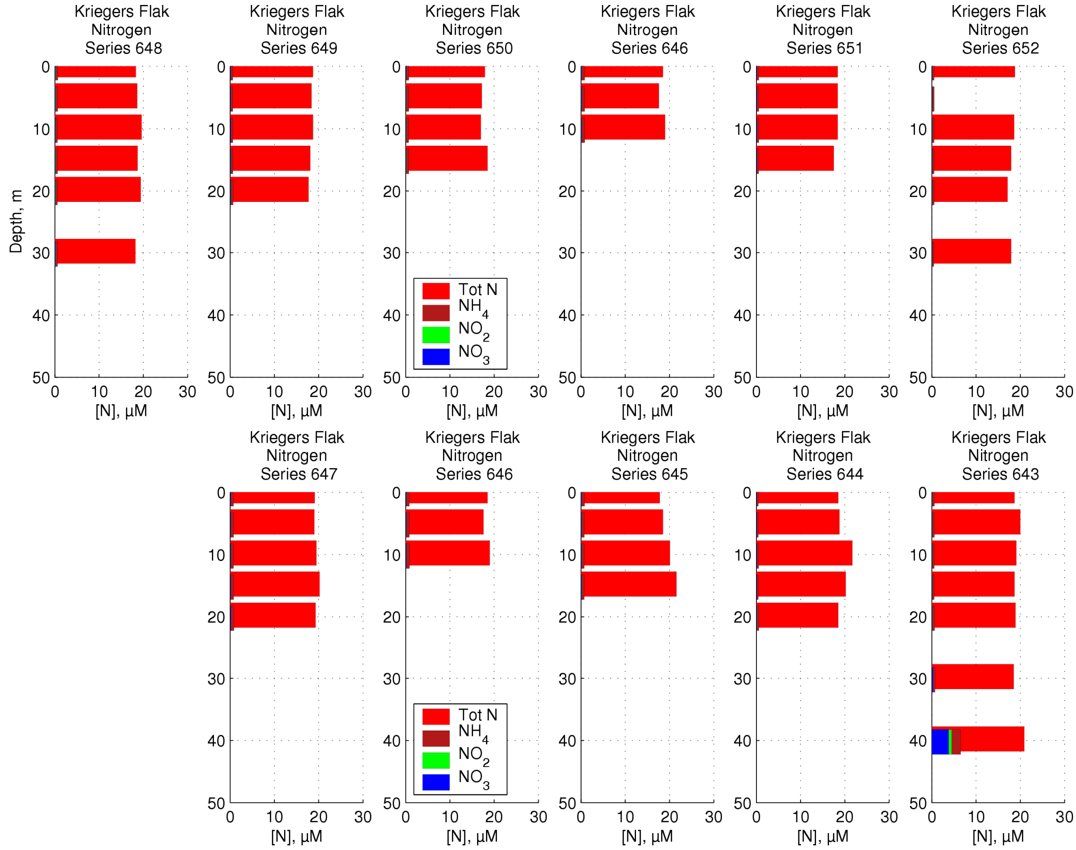


*Figure 49 Nitrogen concentrations around Kriegers Flak*

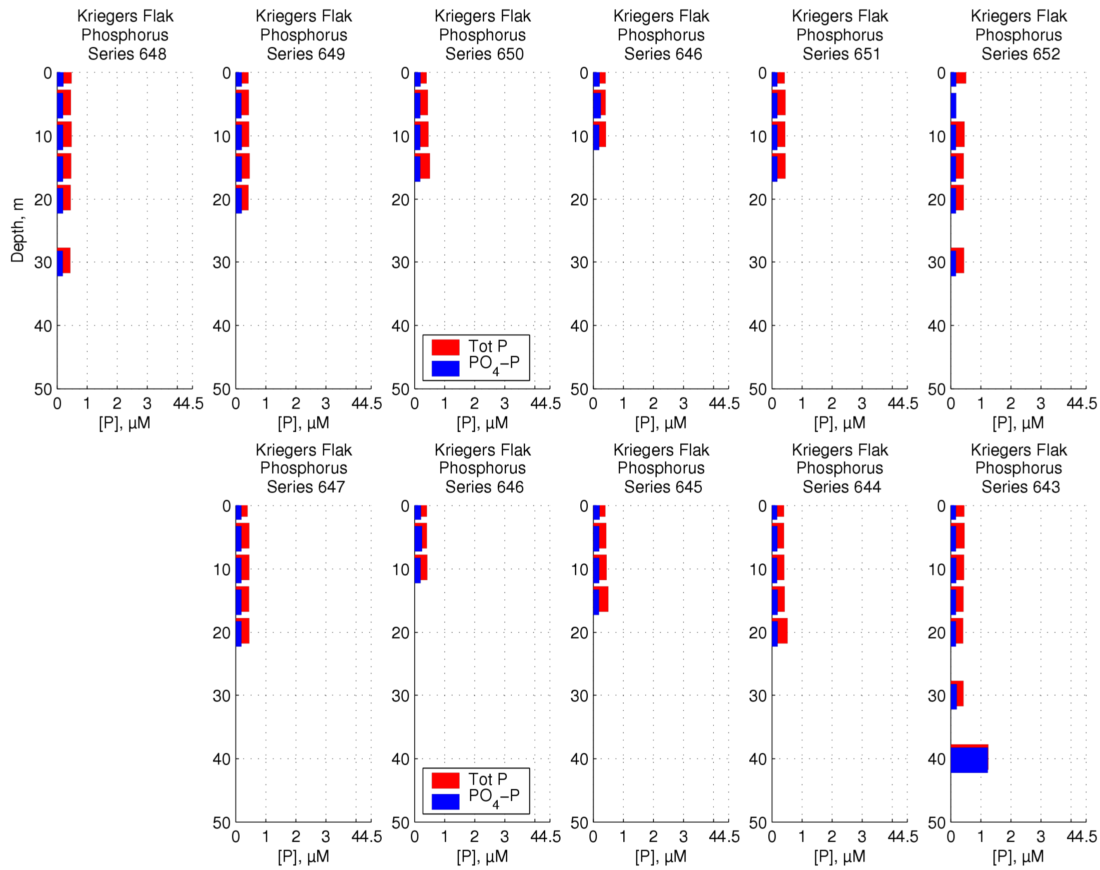


*Figure 50 Phosphorus concentrations around Kriegers Flak*

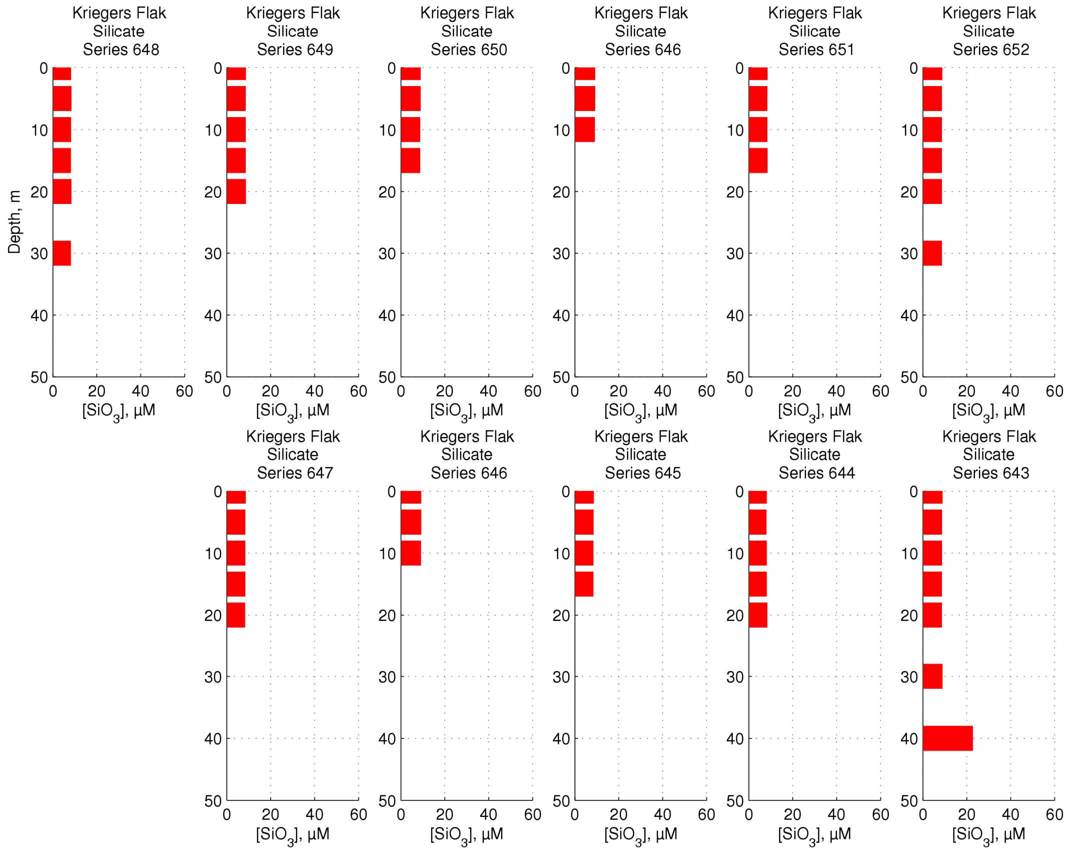


*Figure 51 Silicate concentrations in the vicinity of Kriegers Flak*

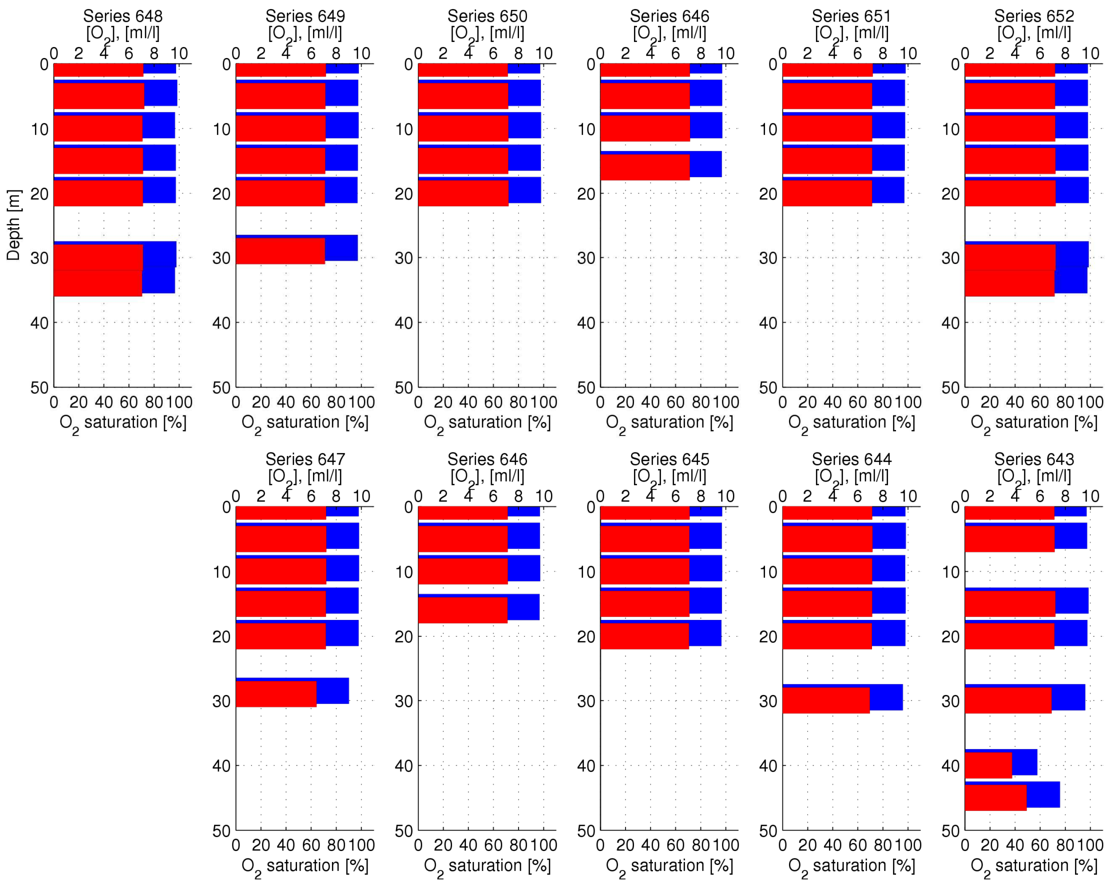


*Figure 52 Oxygen concentrations and saturation in the vicinity of Kriegers Flak*

## Ölands Södra Grund

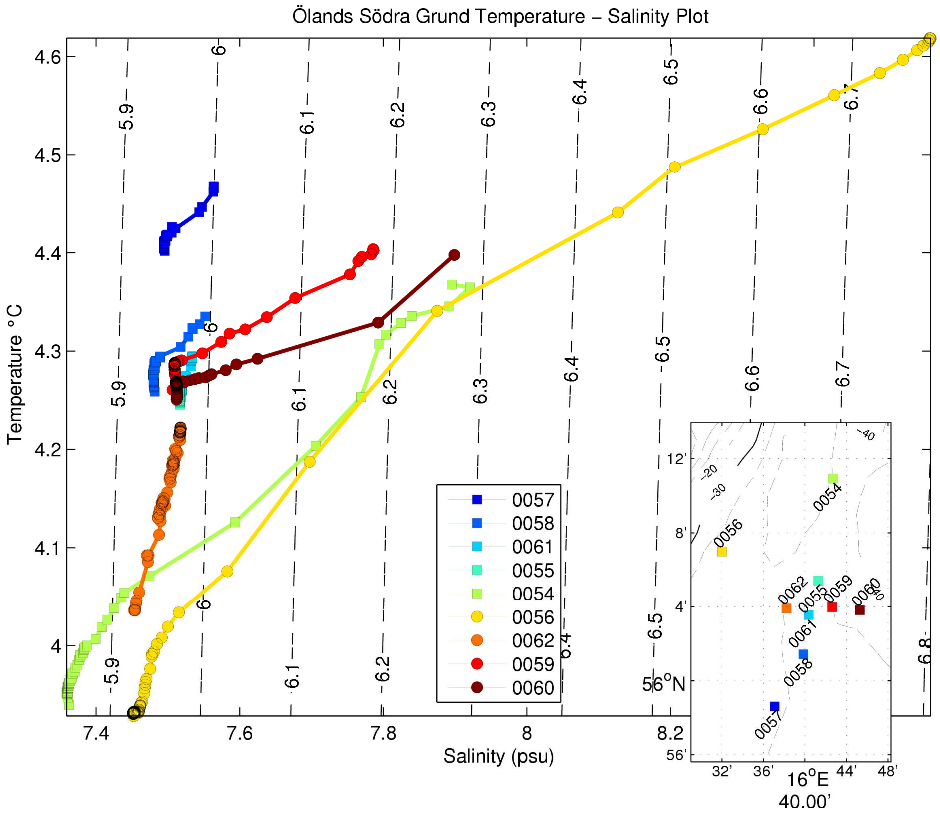


*Figure 53 Ölands Södra Grund temperature – salinity relationship*

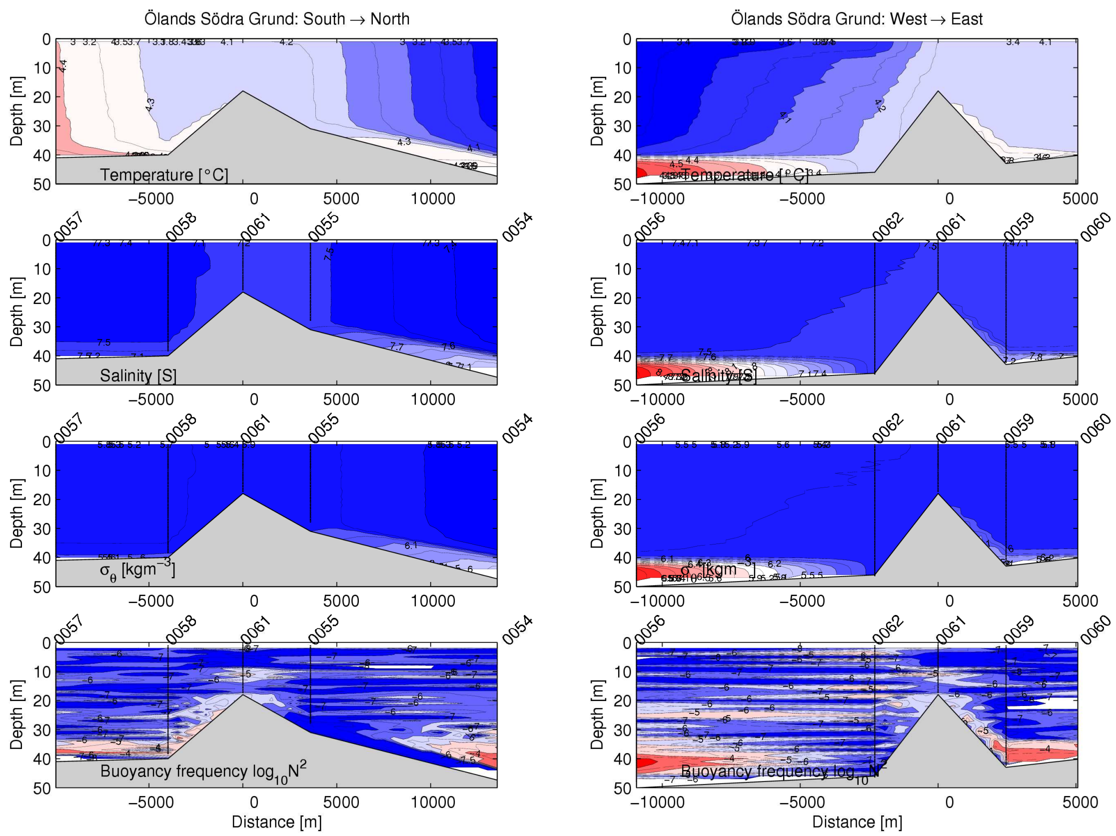


*Figure 54 Gridded hydrographic parameters across Ölands Södra Grund.*

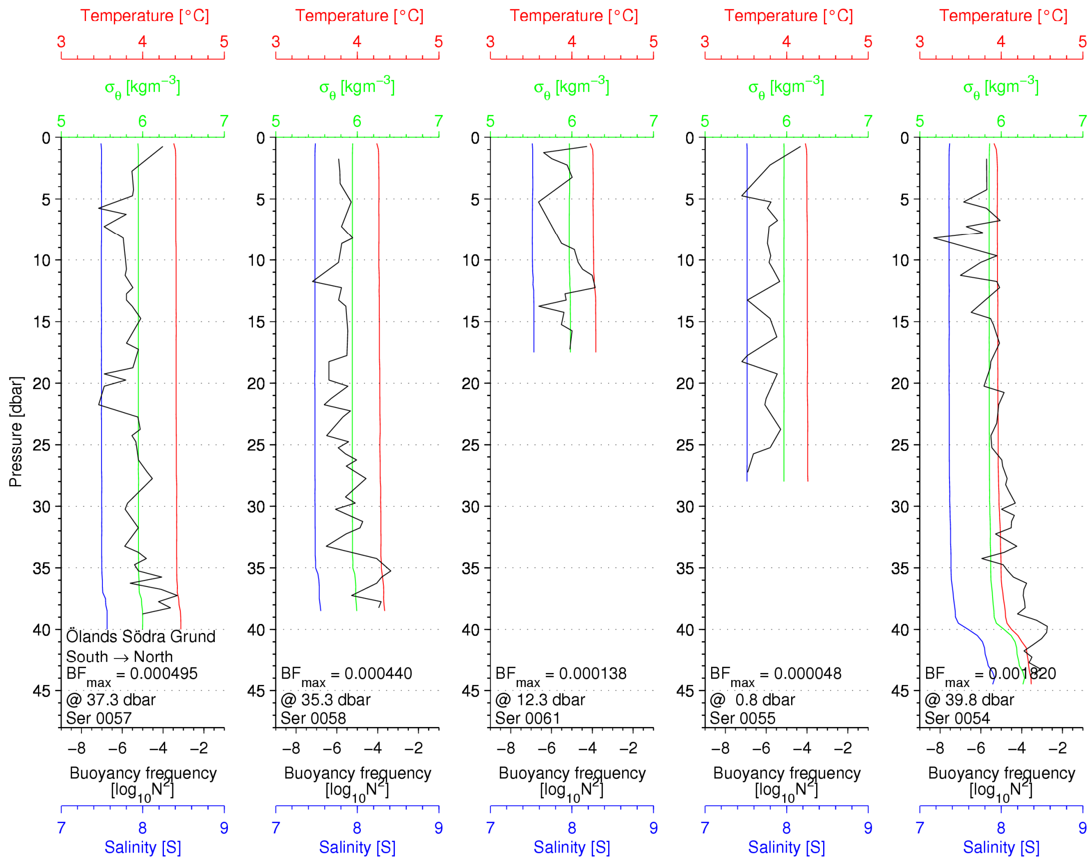


*Figure 55 CTD profiles south – north across Ölands Södra Grund*

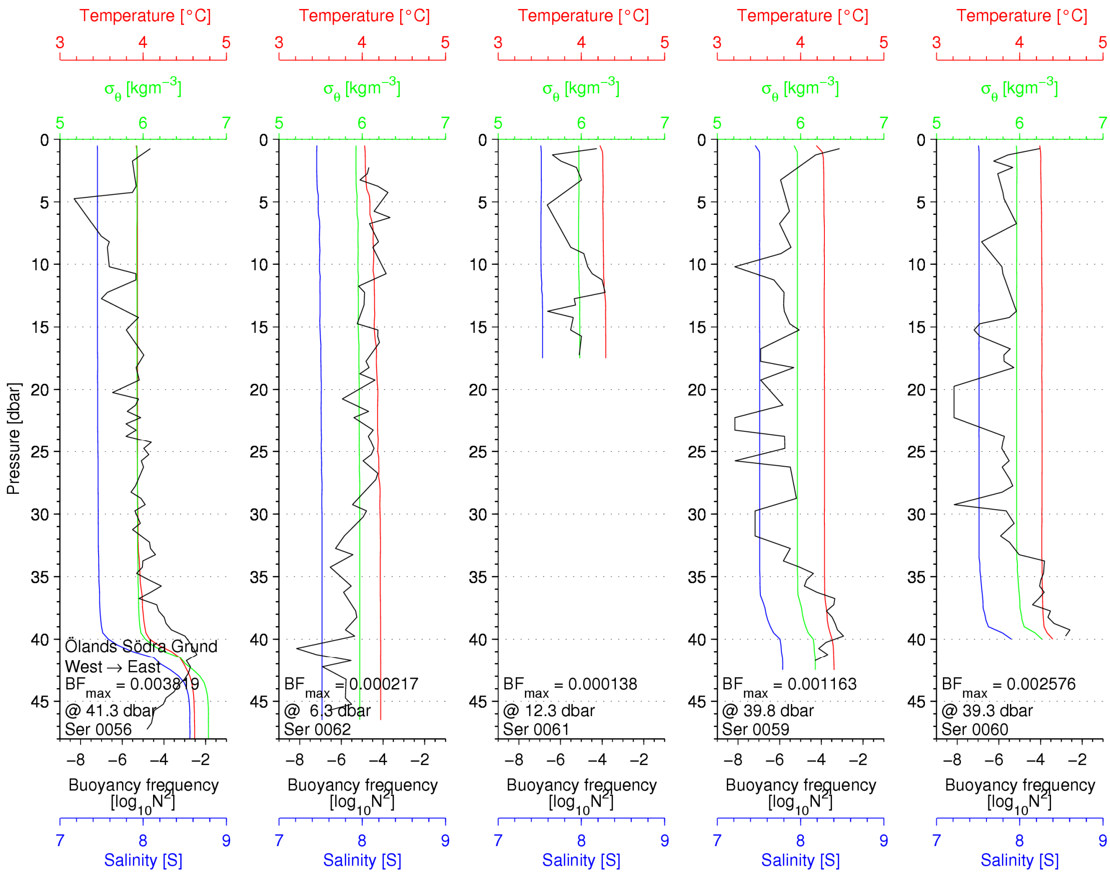


*Figure 56 CTD profiles from west – east across Ölands Södra Grund*

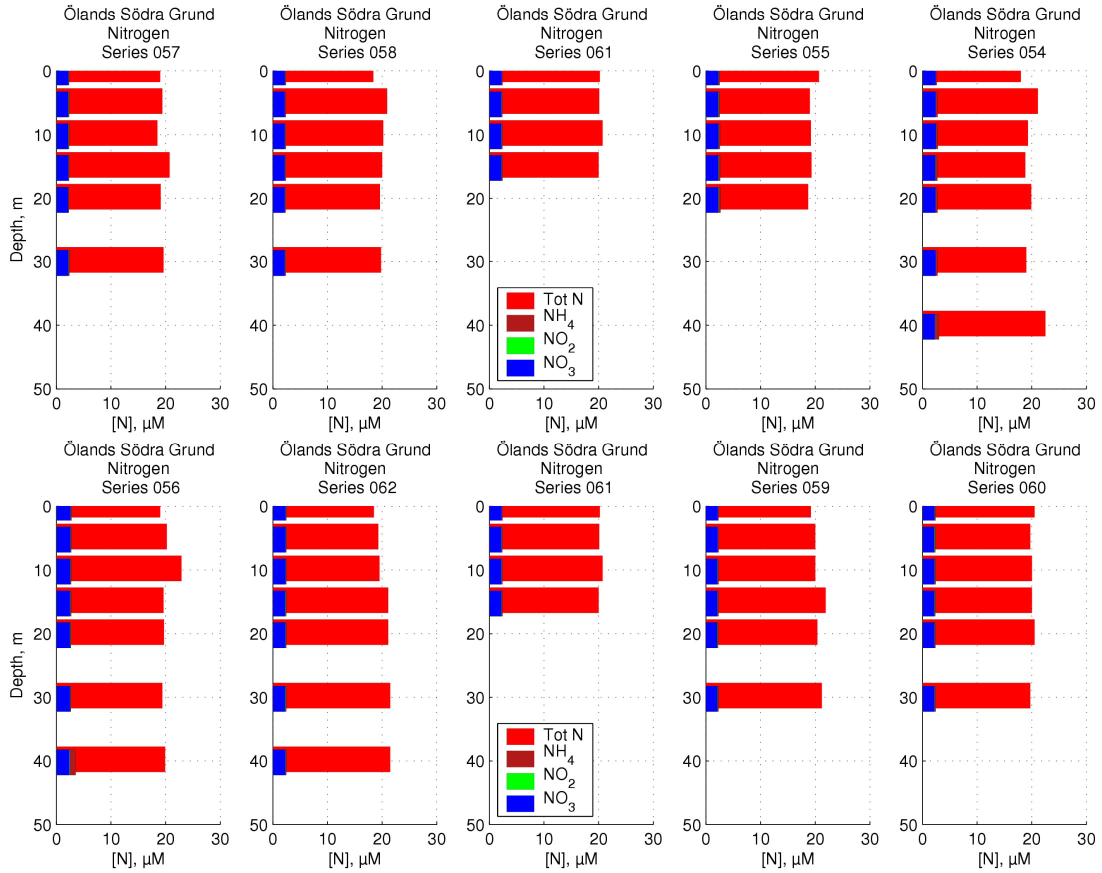


*Figure 57 Nitrogen concentrations around Ölands Södra Grund*

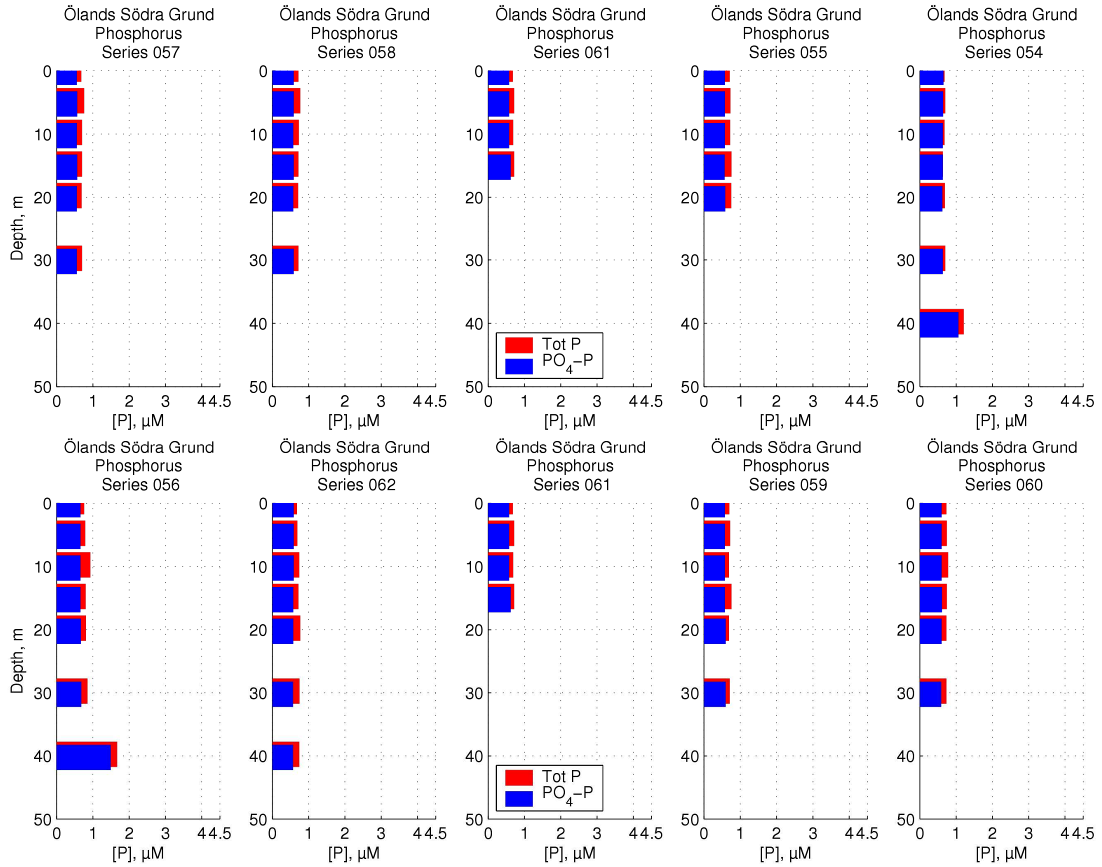


*Figure 58 Phosphorus concentrations around Ölands Södra Grund*

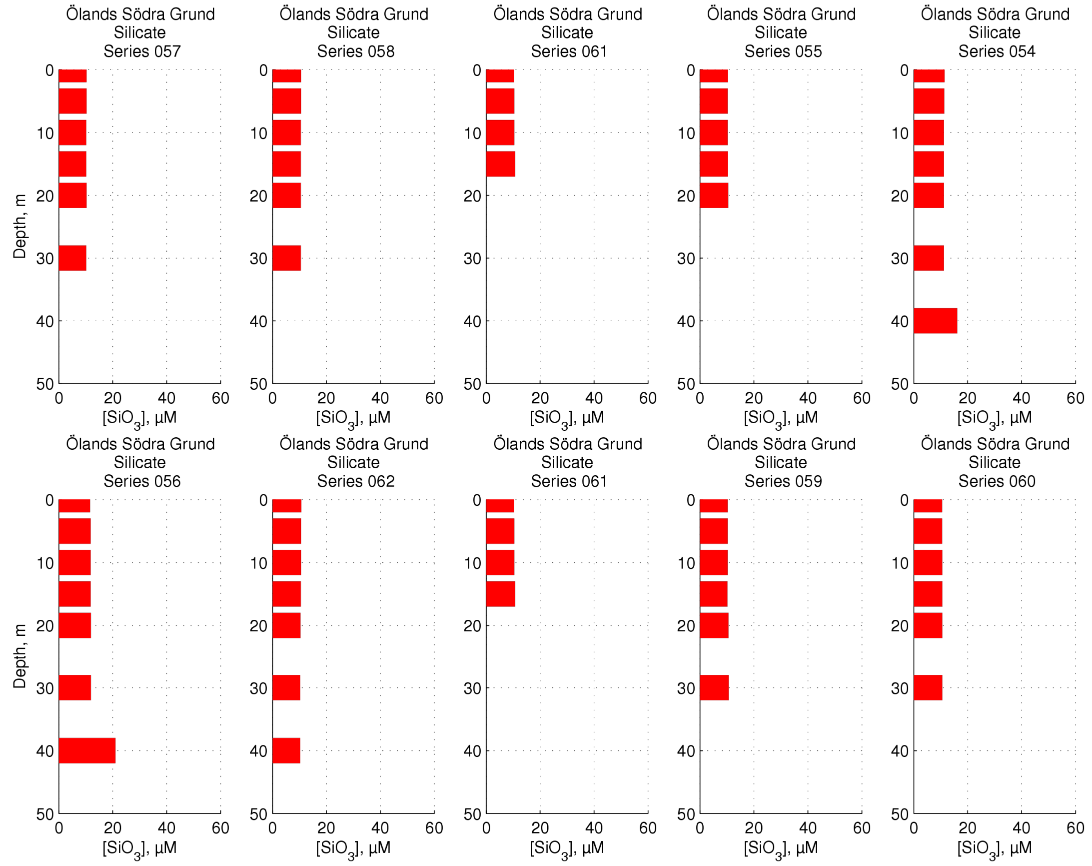


*Figure 59 Silicate concentrations around Ölands Södra Grund*

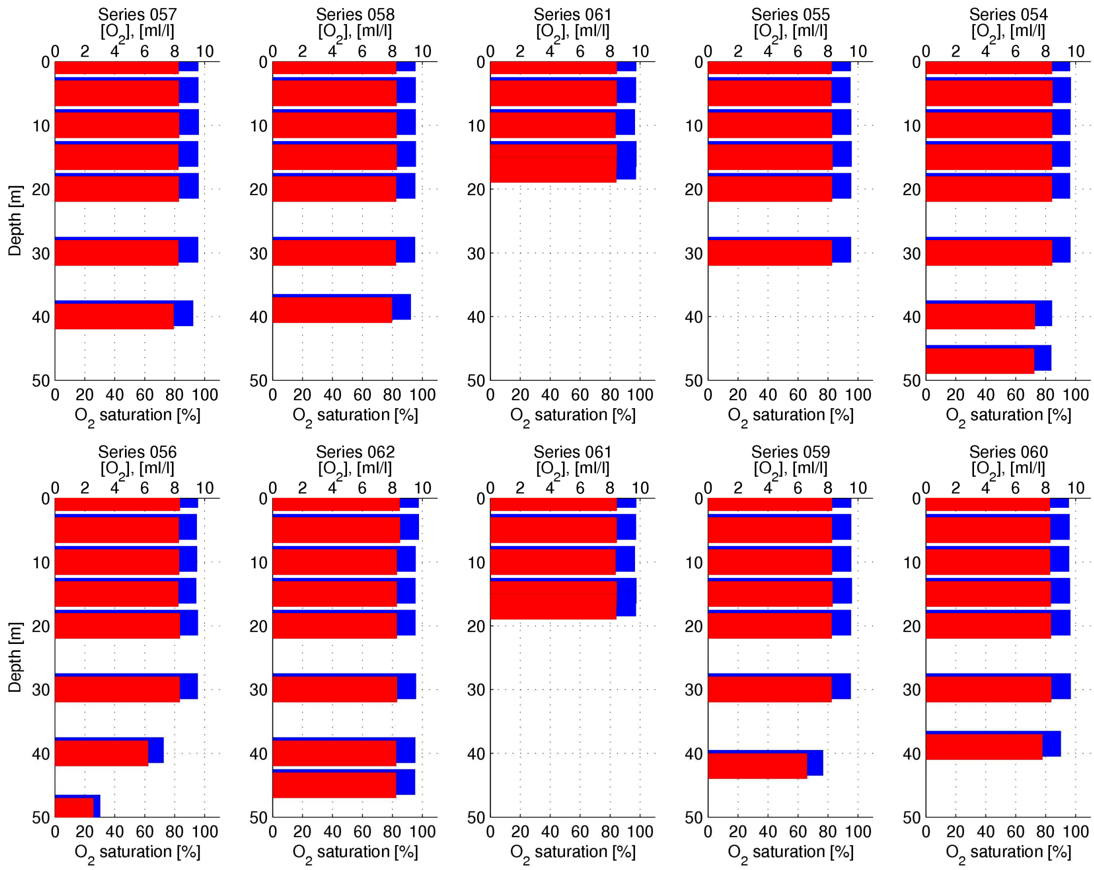


*Figure 60 oxygen concentration (red) and saturation (blue) around Ölands Södra Grund*

## Södra Midsjöbank

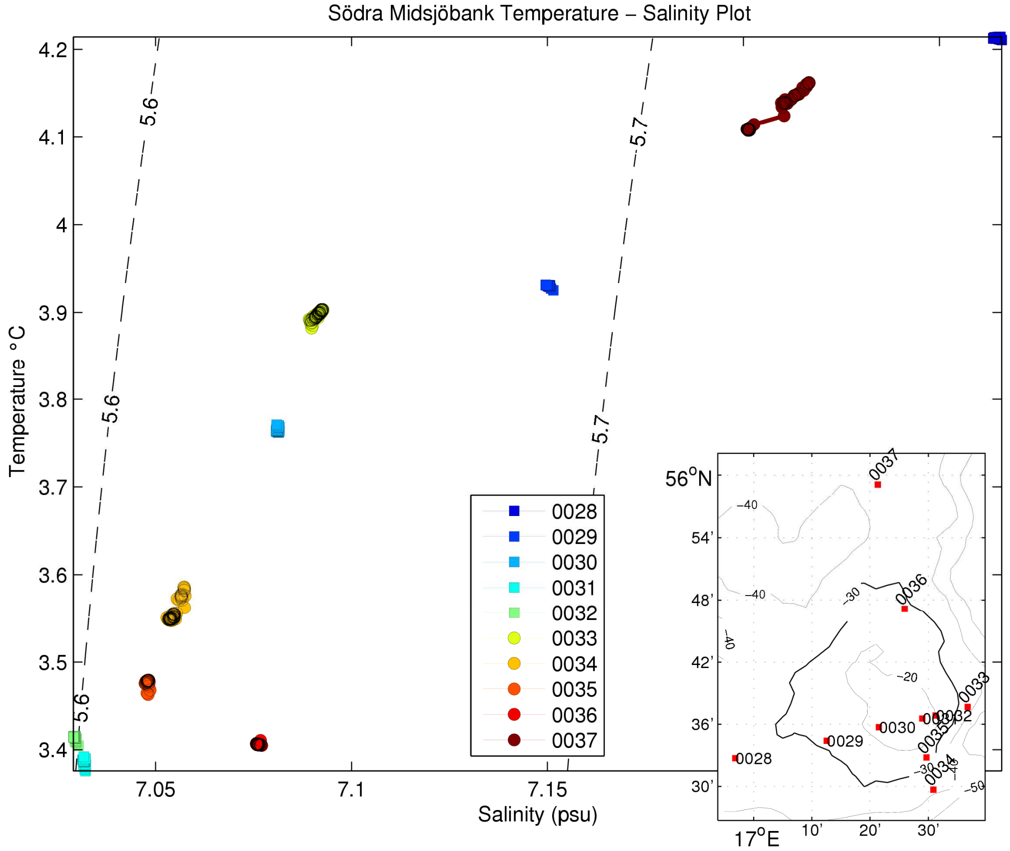


*Figure 61 Temperature – salinity plot across Södra Midsjöbank*

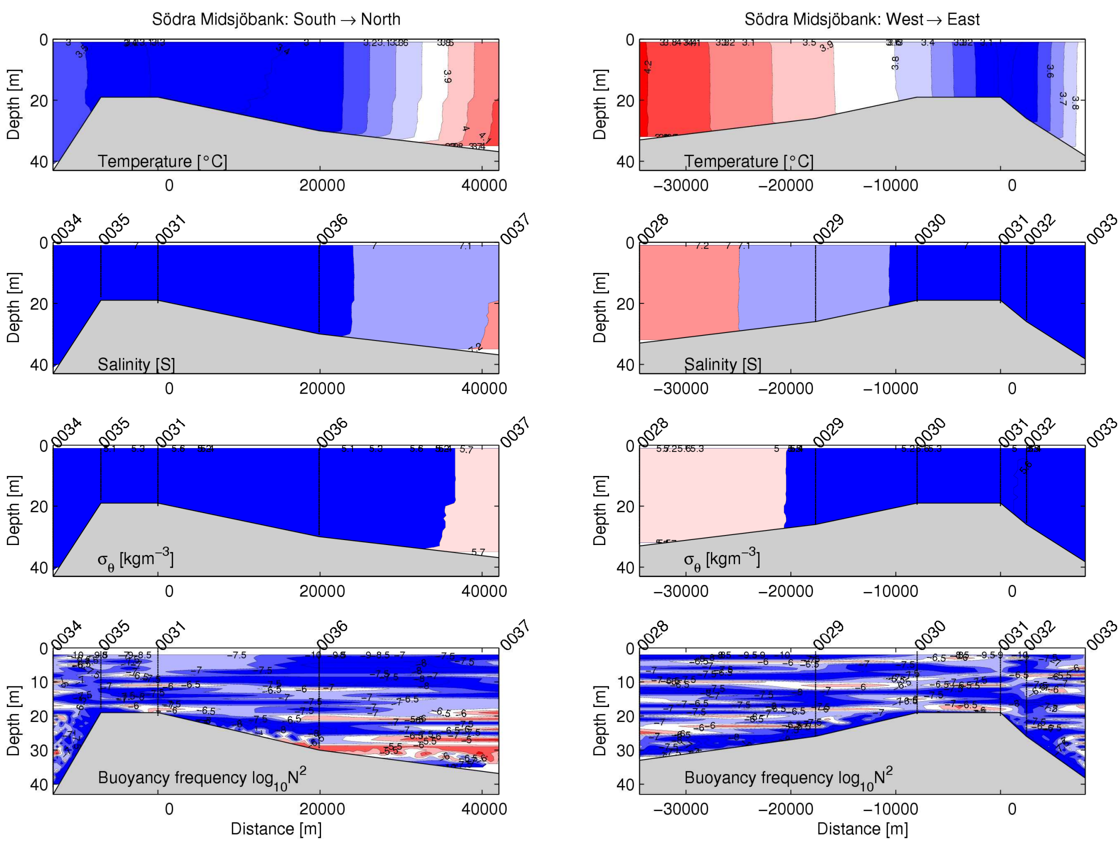


*Figure 62 Gridded hydrographic parameters over Södra Midsjöbank*

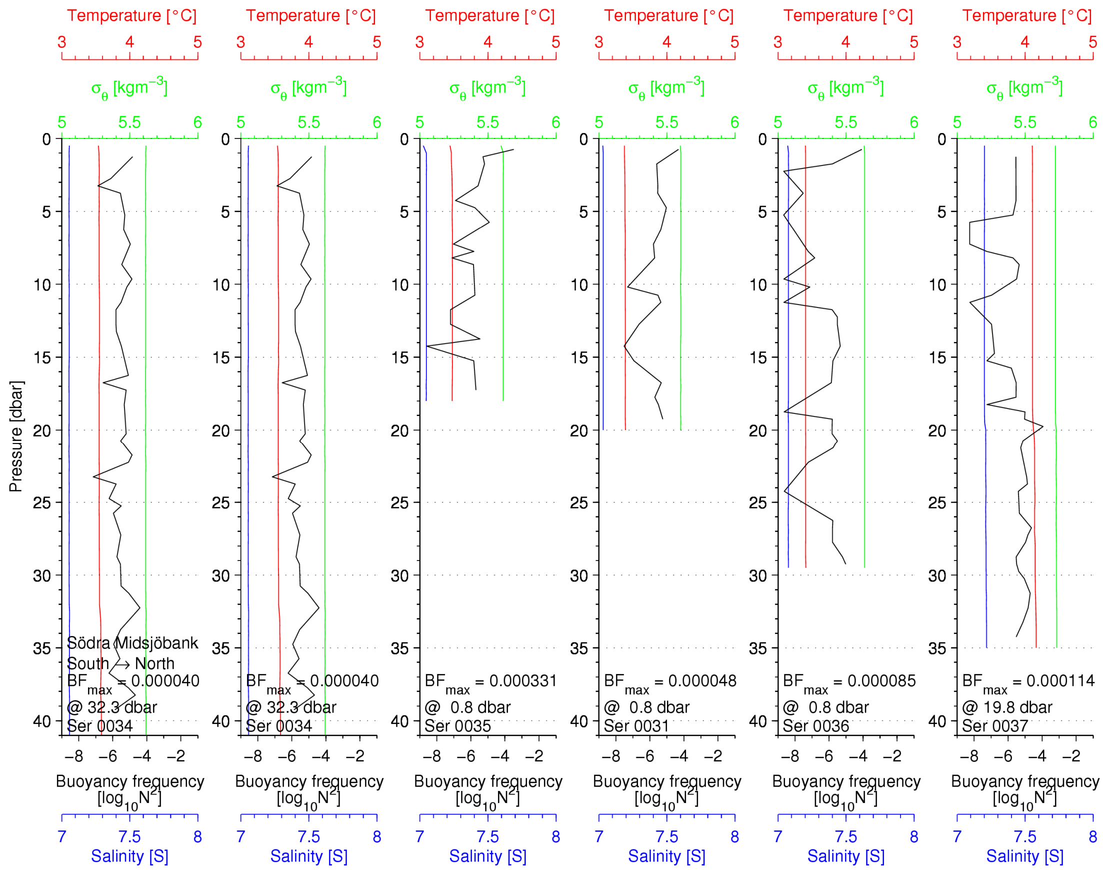


*Figure 63 CTD profiles from south – north transect over Södra Midsjöbank*

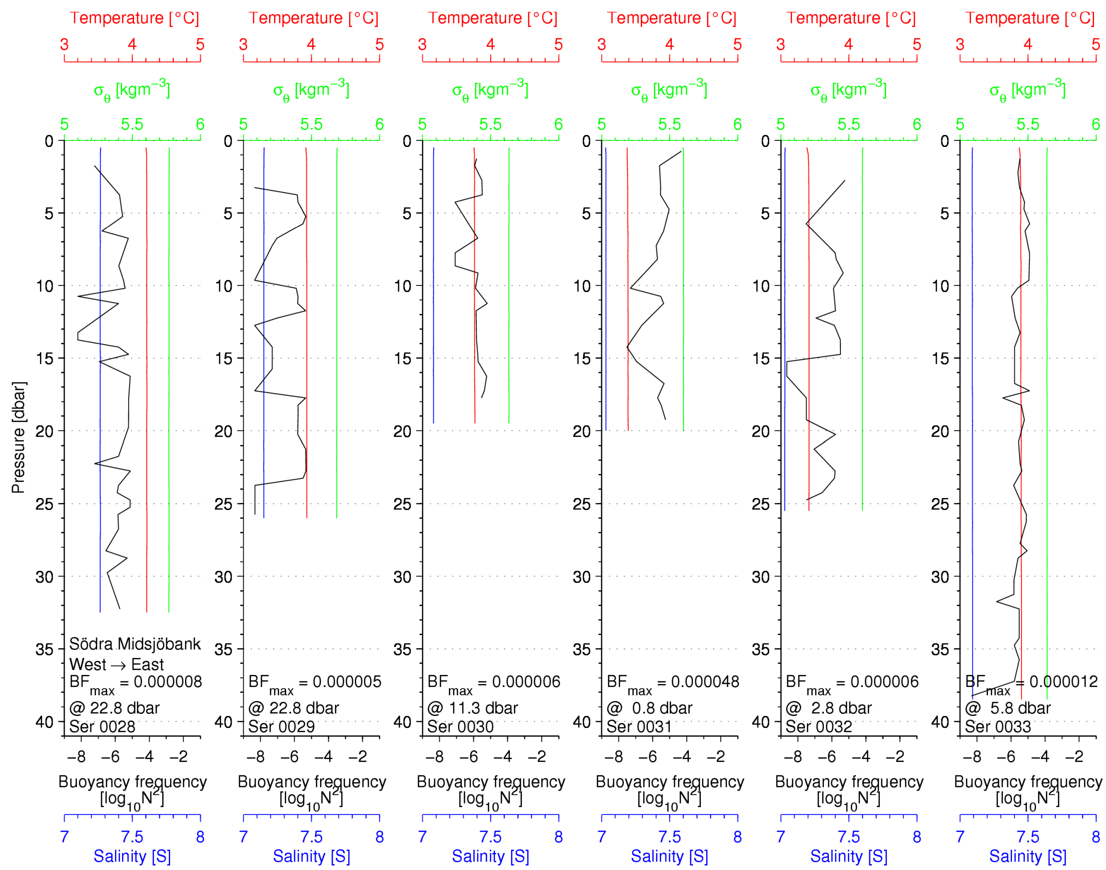


*Figure 64 CTD profiles from west - east transect over Södra Midsjöbank*

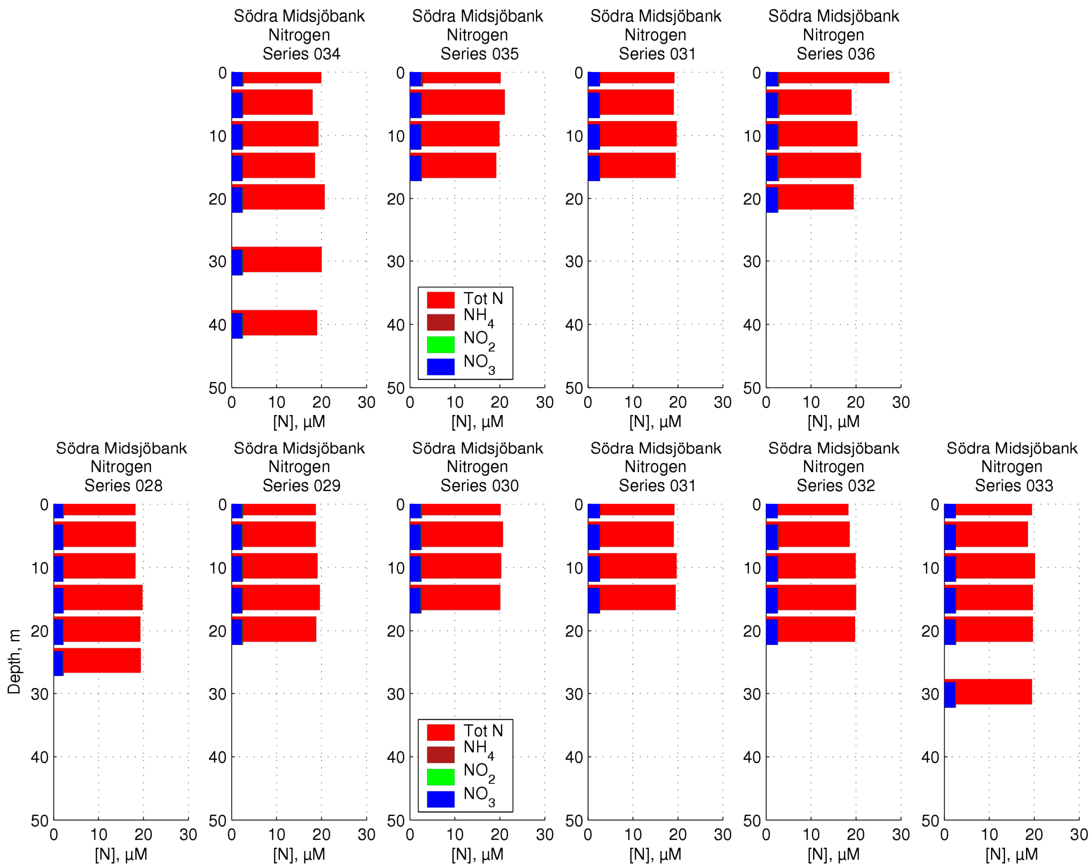


*Figure 65 Nitrogen concentrations over Södra Midsjöbanken*

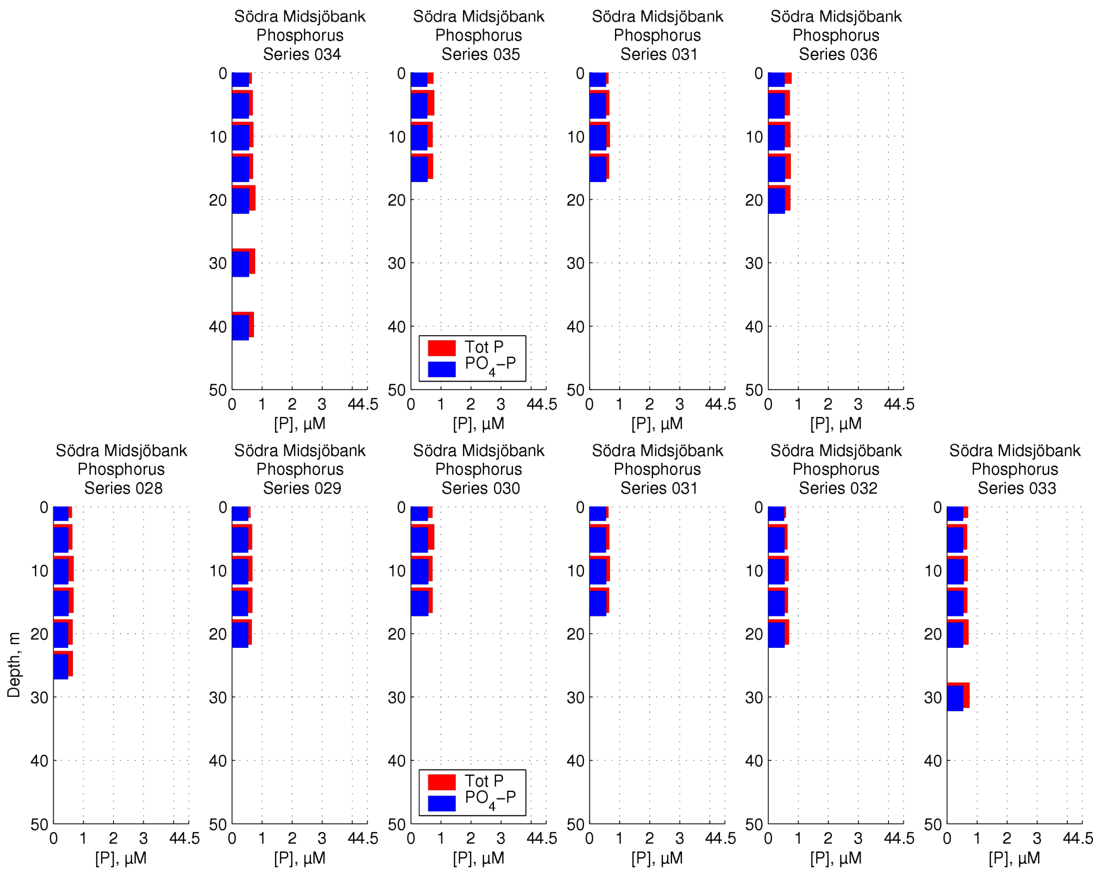


*Figure 66 Phosphorus concentrations over Södra Midsjöbanken*

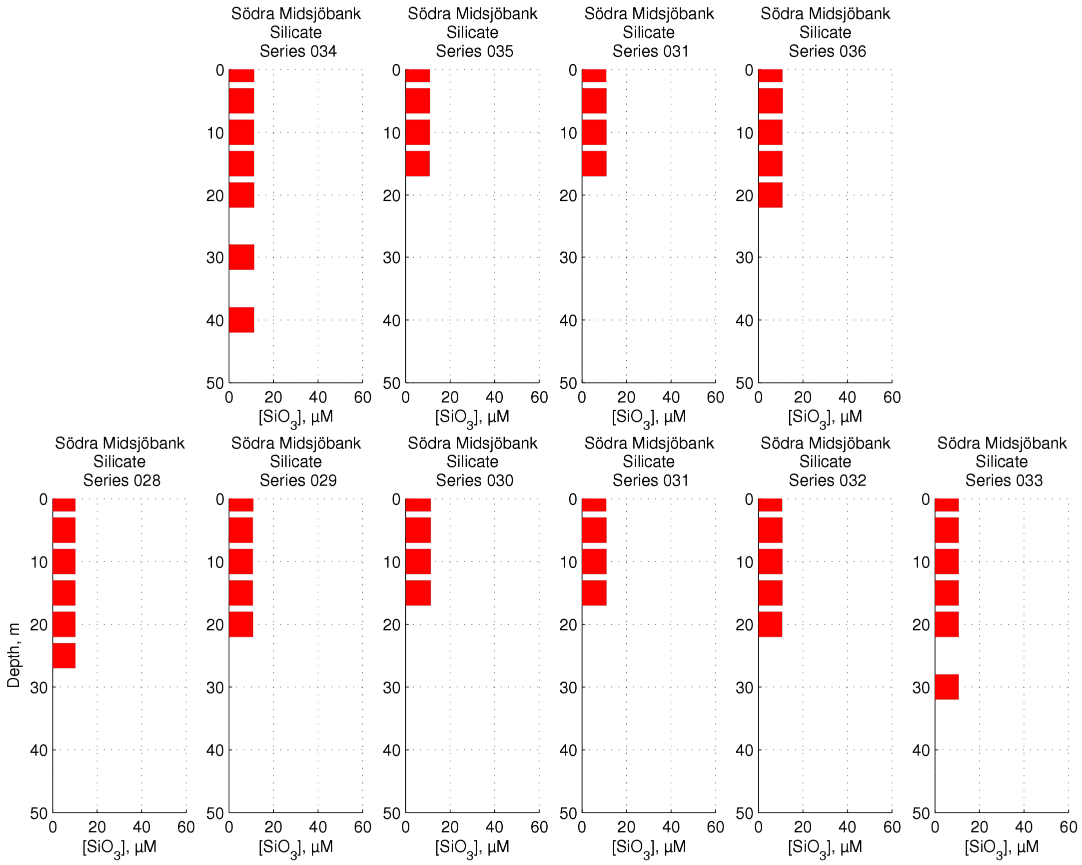


*Figure 67 Silicate concentrations over Södra Midsjöbanken*

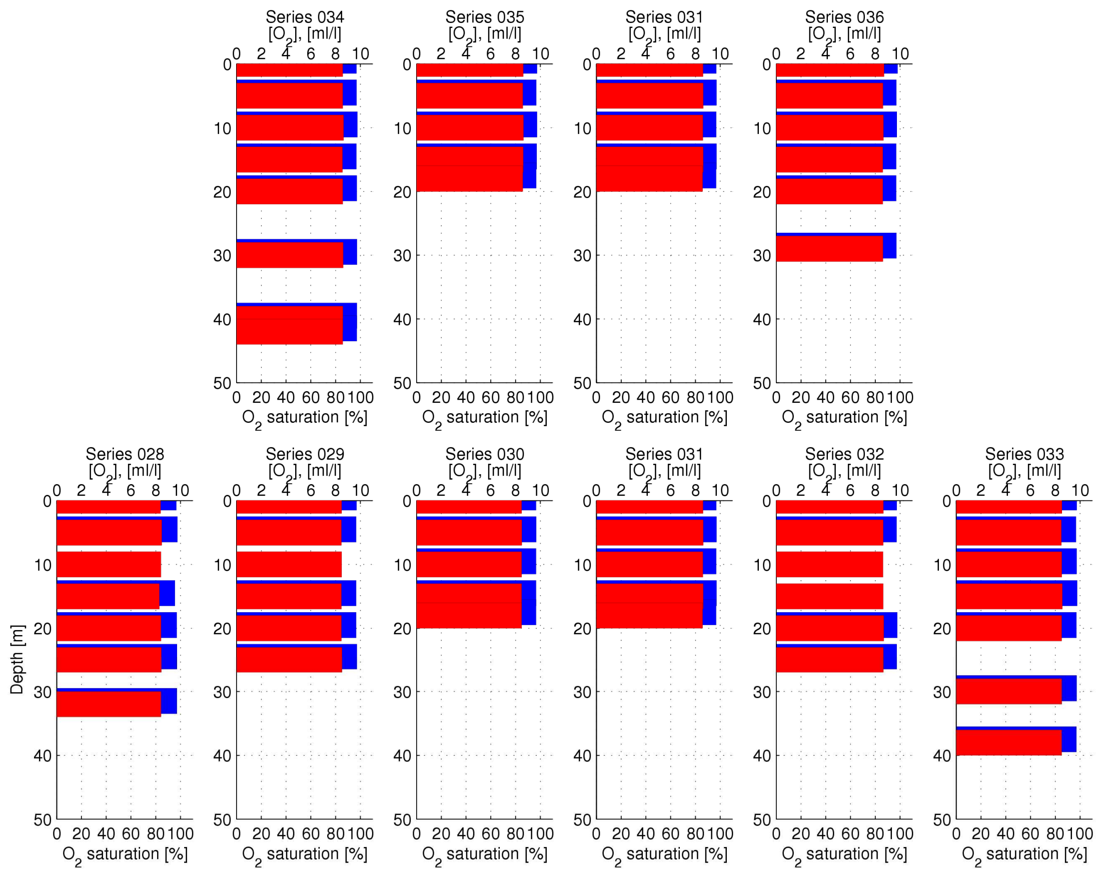


*Figure 68 Oxygen concentrations (red) and saturation (blue) across Södra Midsjöbanken*

## Norra Midsjöbank

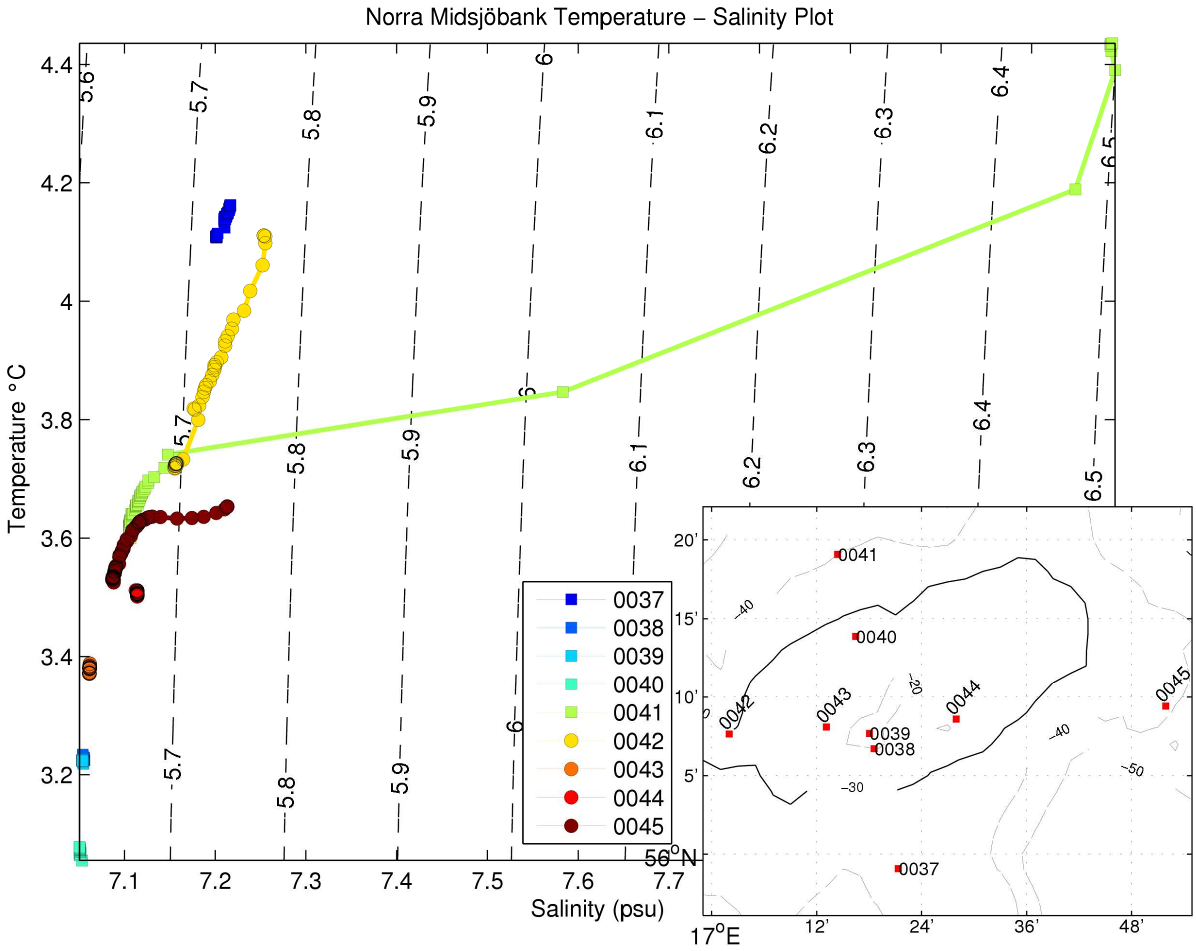


*Figure 69 Temperature – salinity diagram for Norra Midsjöbank*

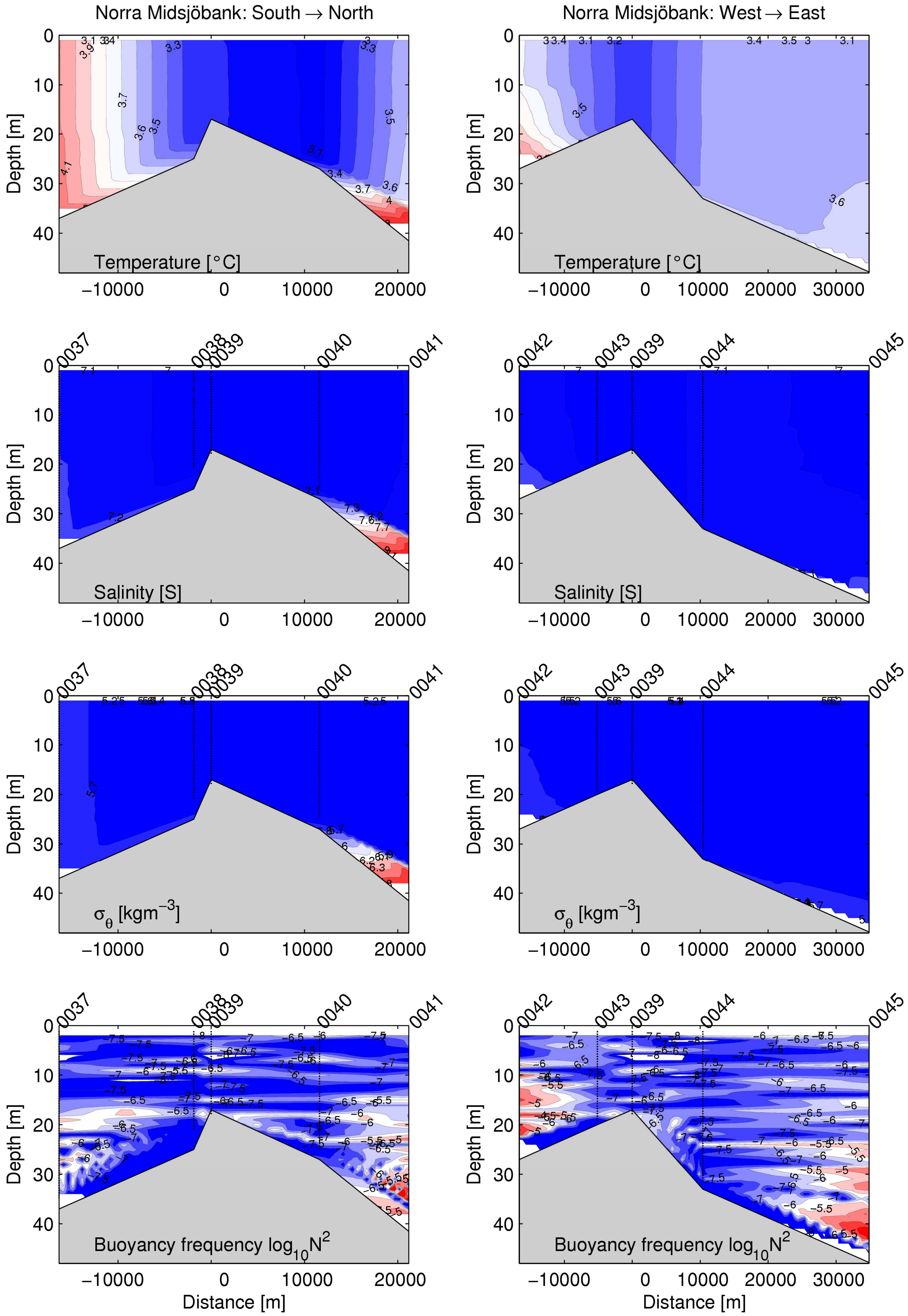


*Figure 70 Gridded hydrographic parameters across Norra Midsjöbank*

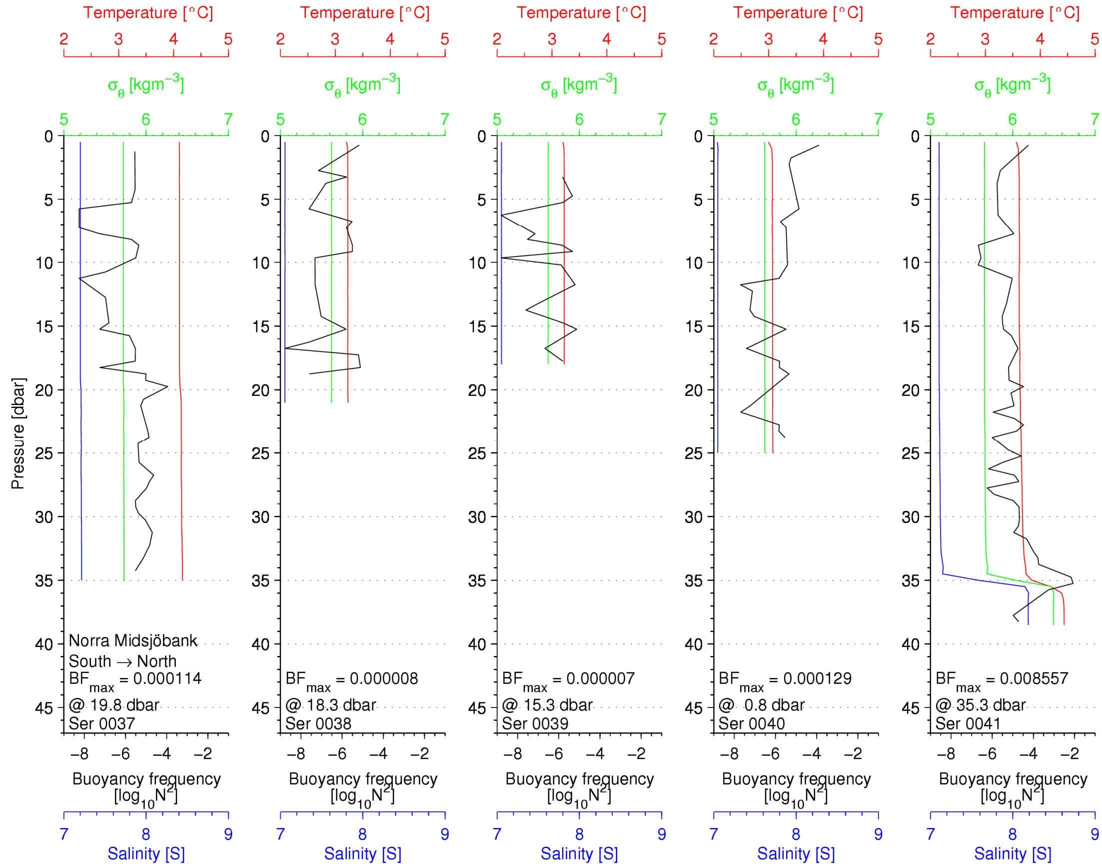


*Figure 71 CTD profiles from south to north across Norra Midsjöbank*

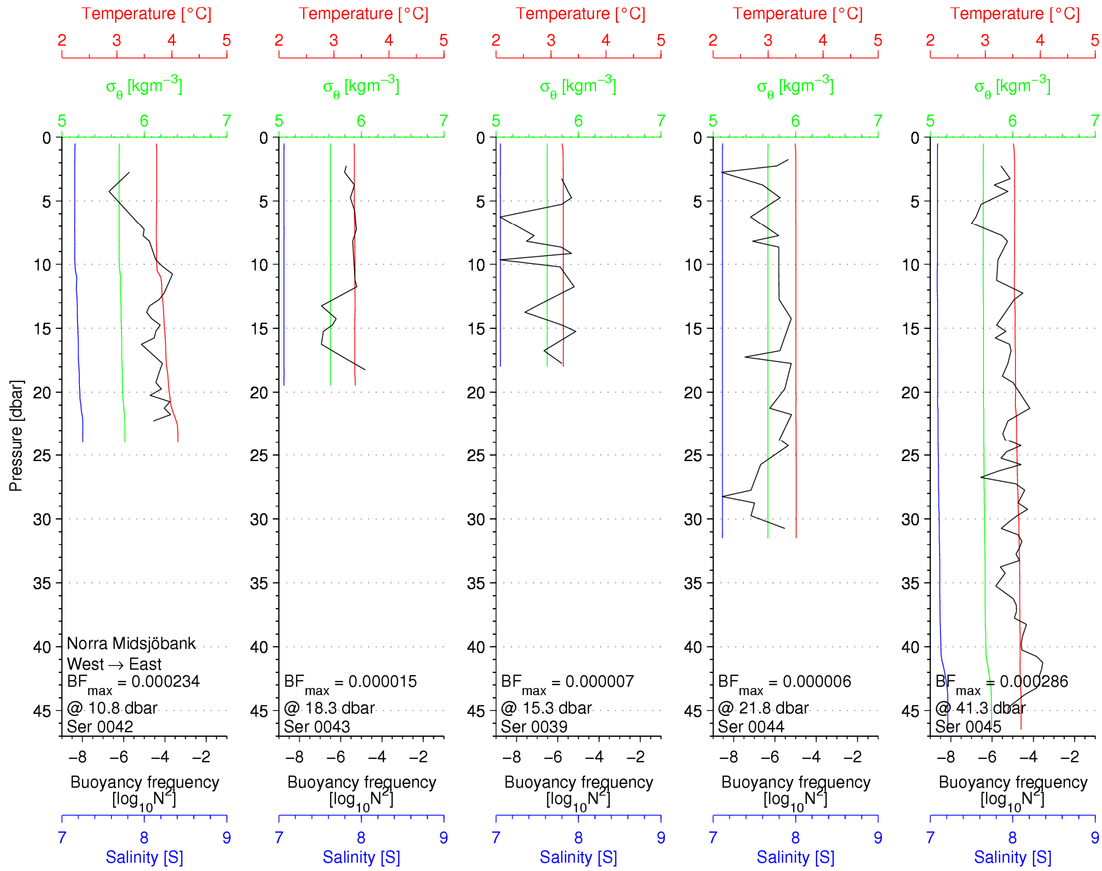


*Figure 72 CTD profiles from west to east across Norra Midsjöbank*

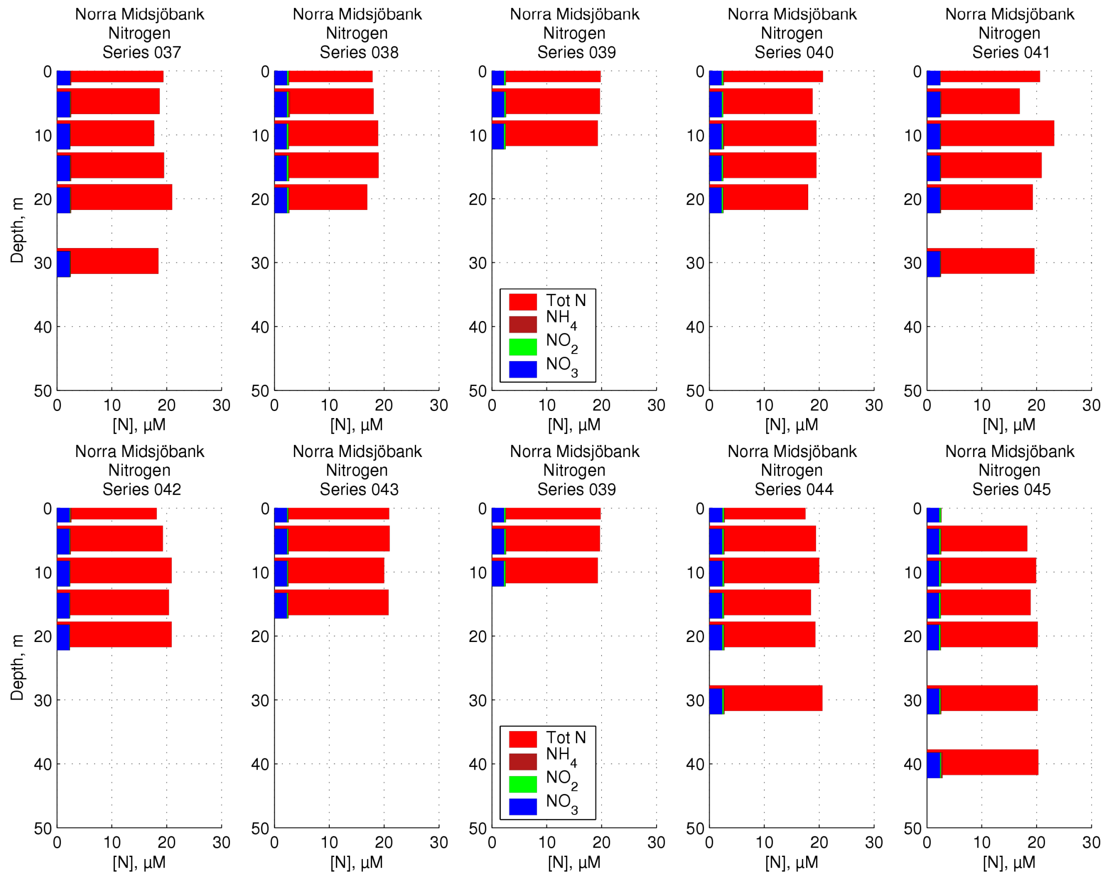


*Figure 73 Nitrogen concentrations over Norra Midsjöbank*

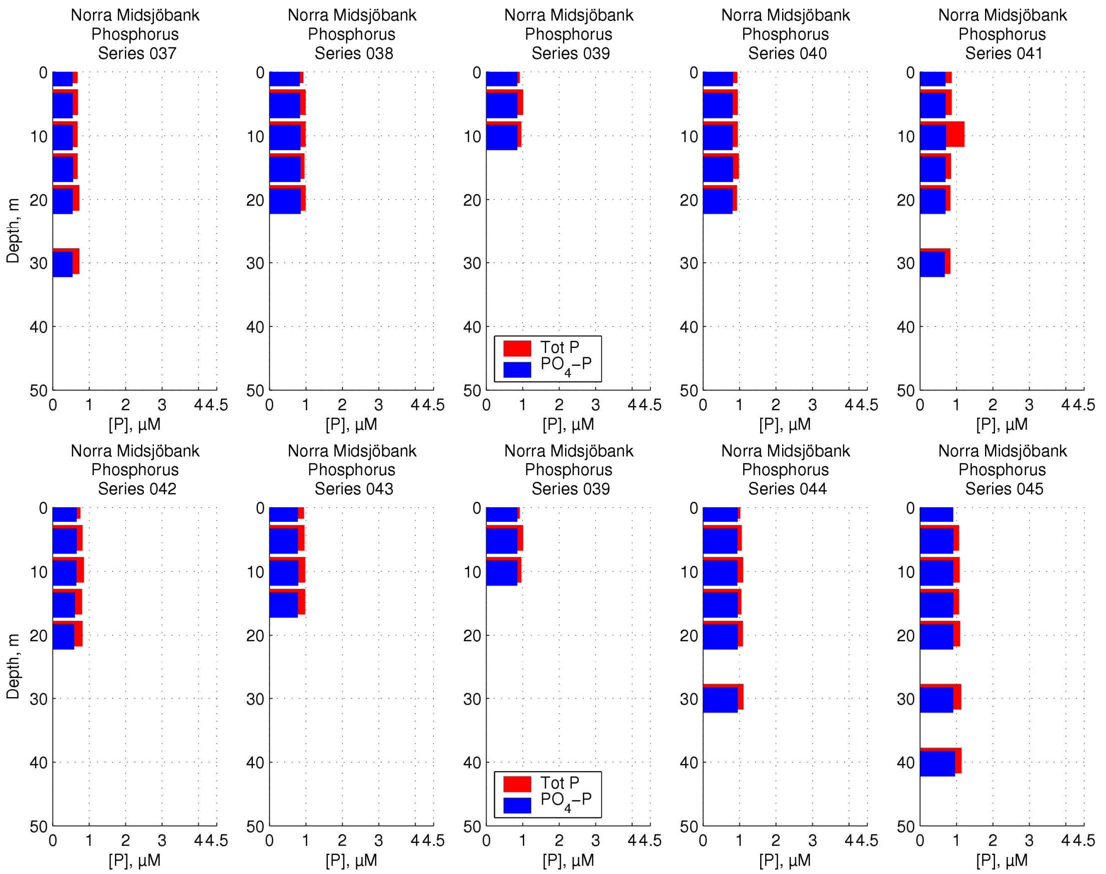


*Figure 74 Phosphorus concentrations over Norra Midsjöbank*

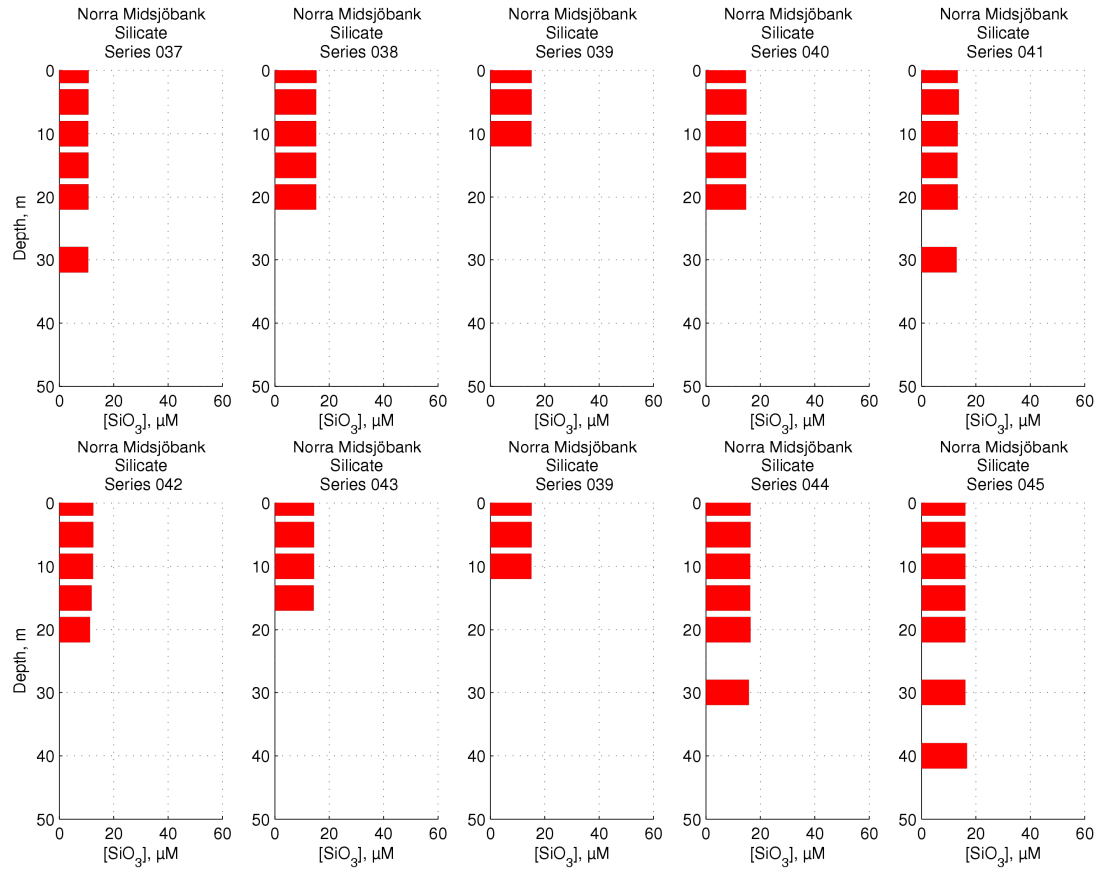


*Figure 75 Silicate concentrations across Norra Midsjöbank*

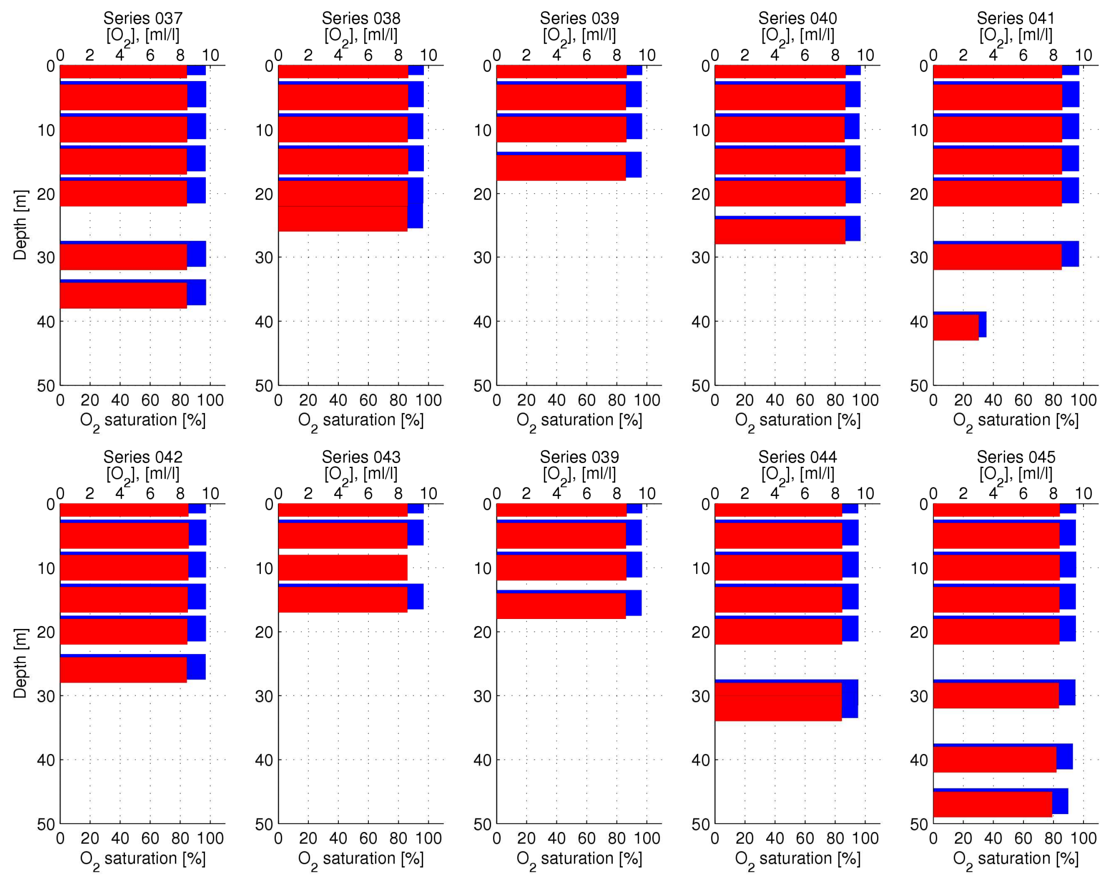


*Figure 76 Oxygen concentrations (red) and saturation (blue) over Norra Midsjöbank*

## Hoburg Bank

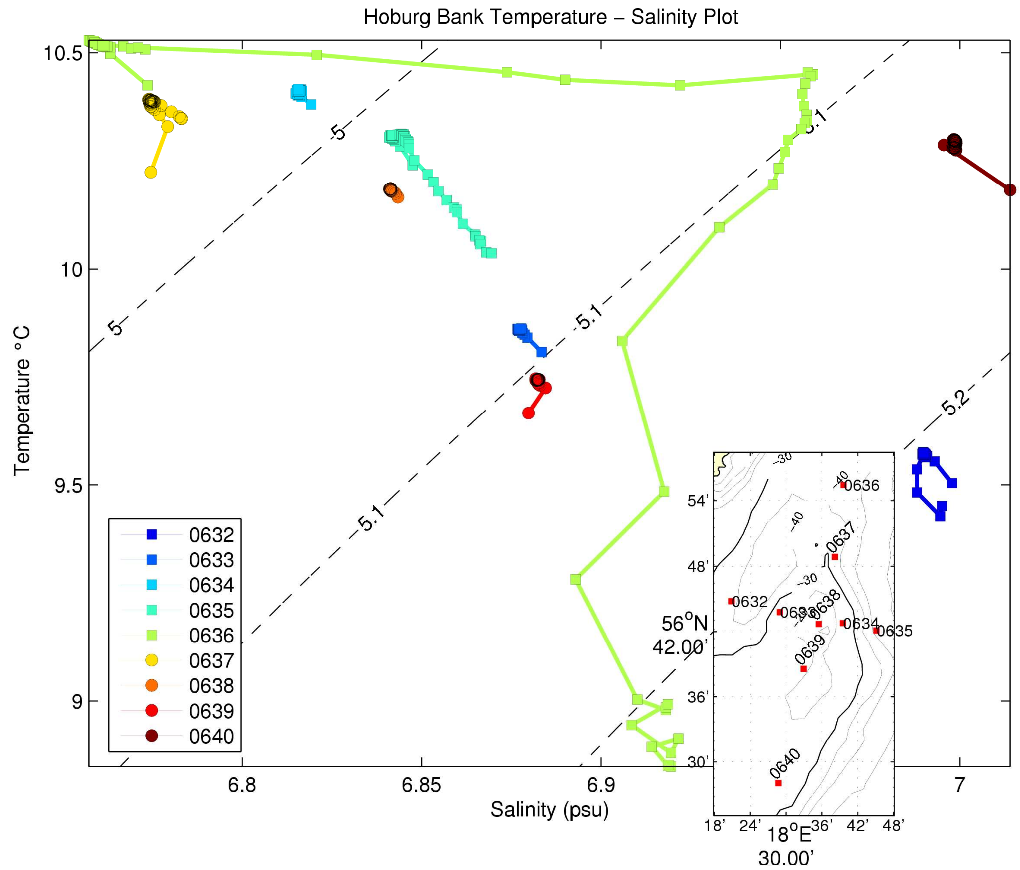


*Figure 77 Temperature Salinity data from Hoburg Bank*

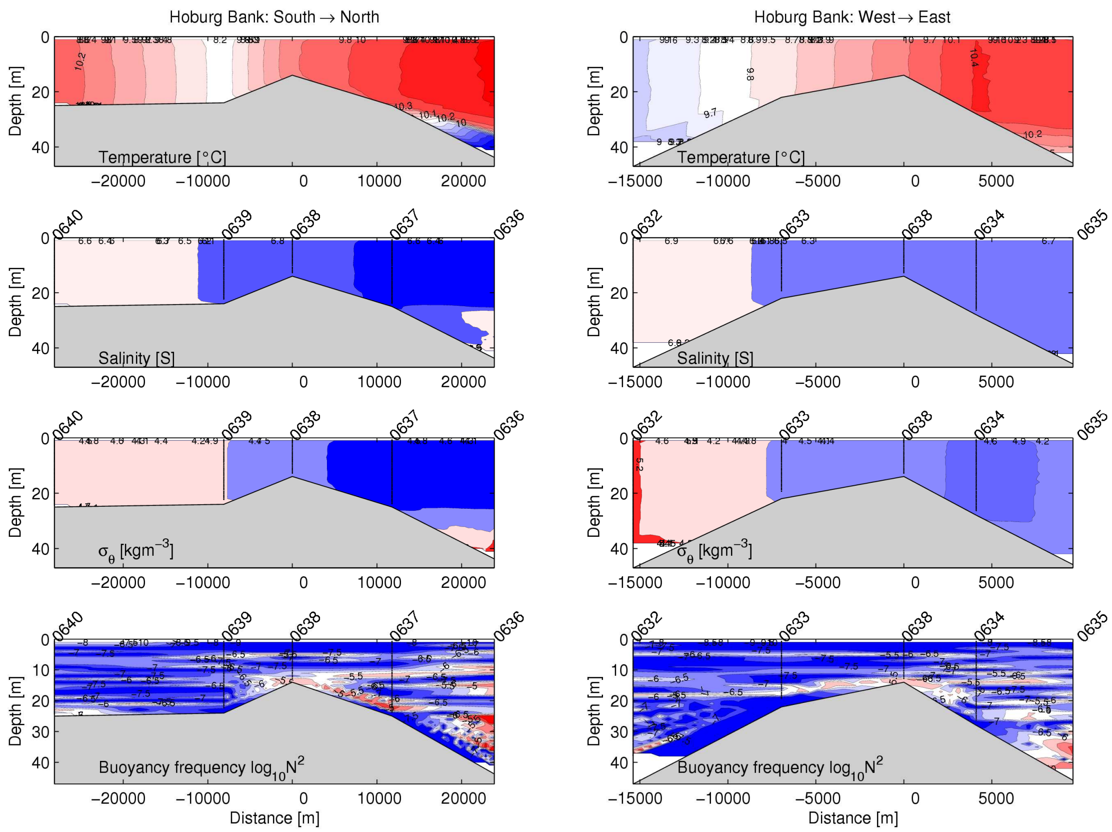


*Figure 78 Gridded hydrographic parameters across the Hoburg Bank*

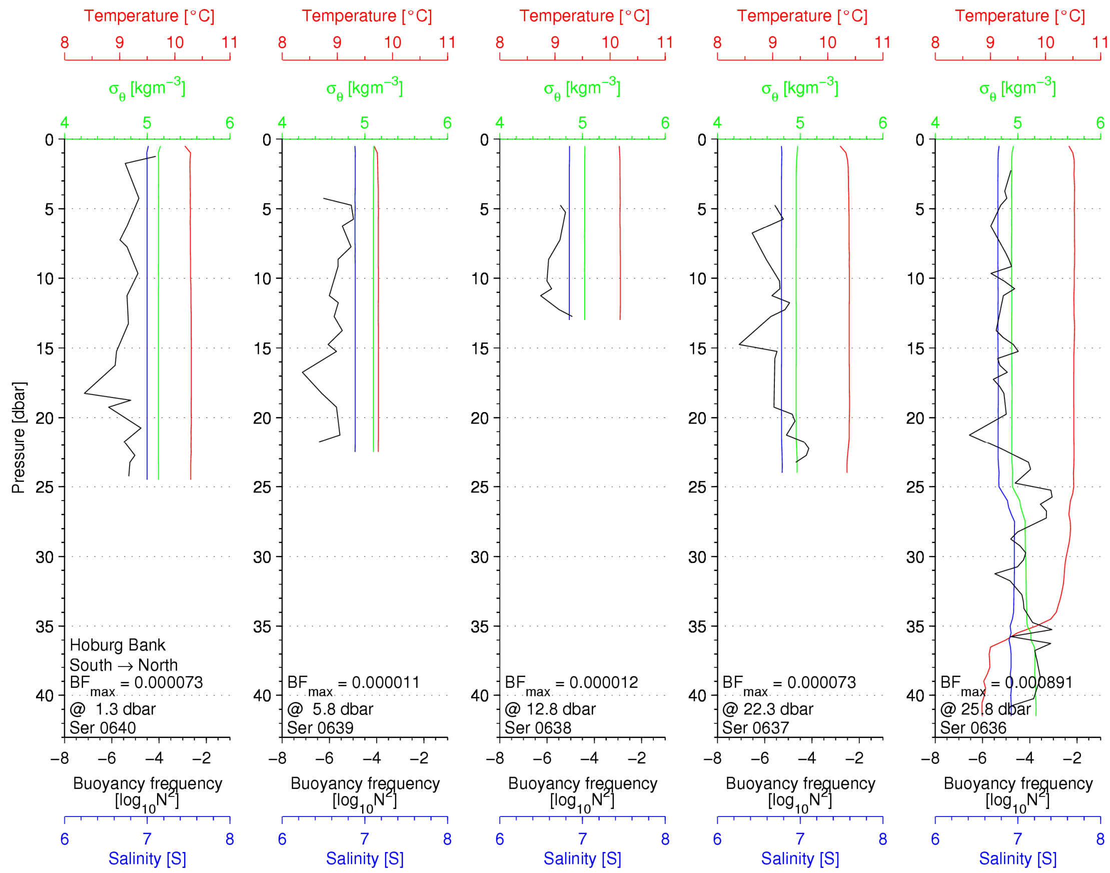


*Figure 79 CTD profiles from south to north across Hoburg Bank*

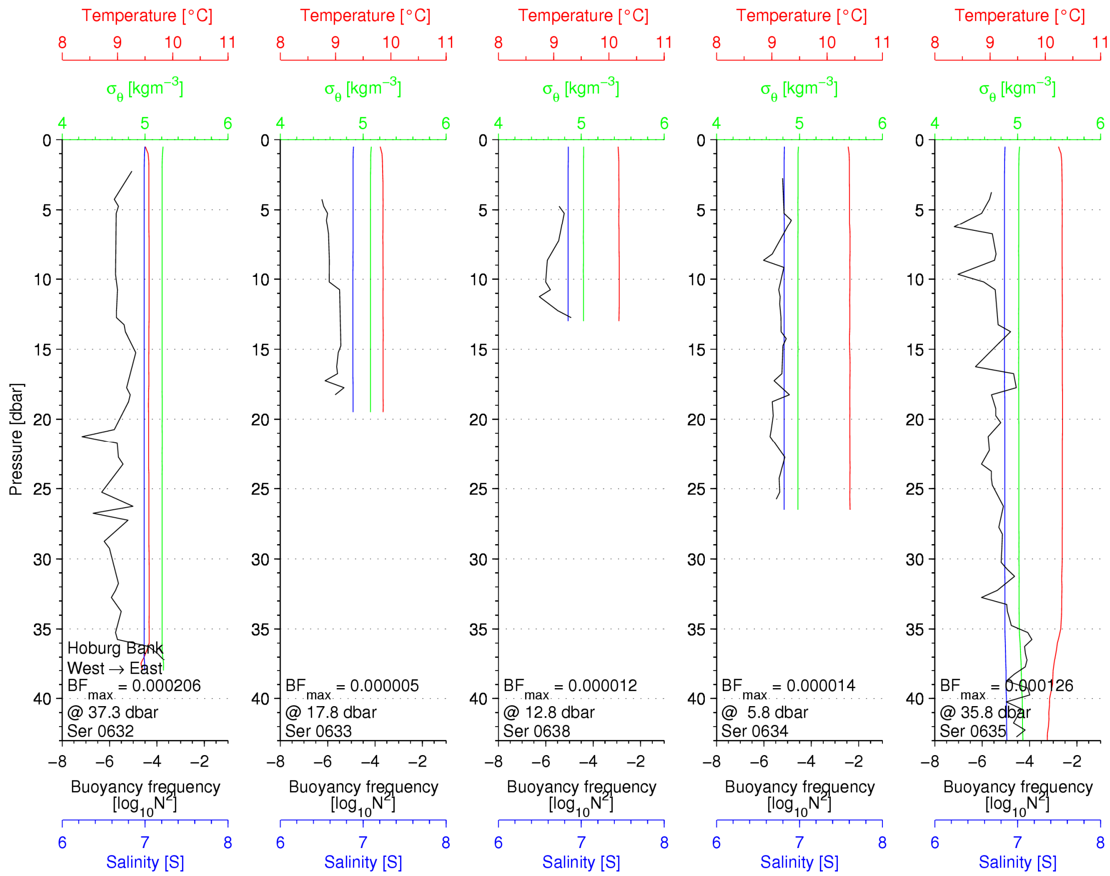


*Figure 80 CTD profiles from west to east across Hoburg Bank*

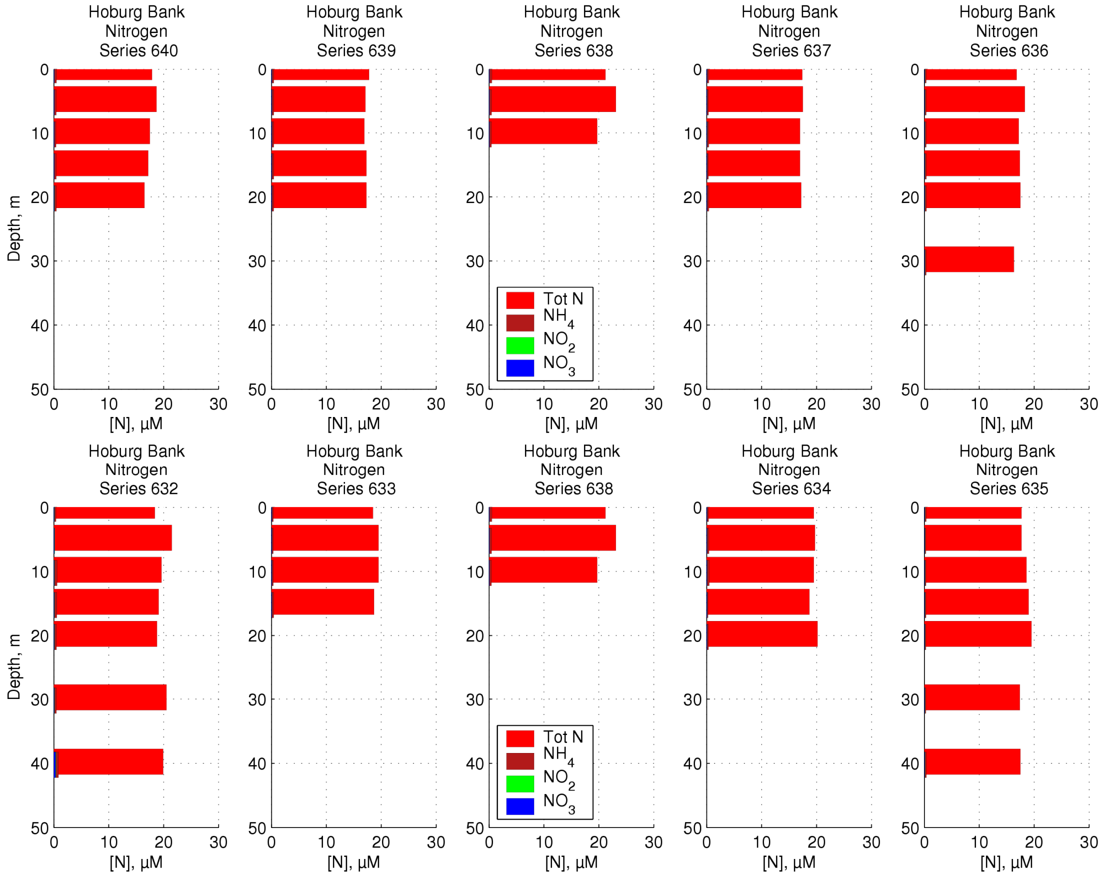


*Figure 81 Nitrogen concentrations over the Hoburg Bank*

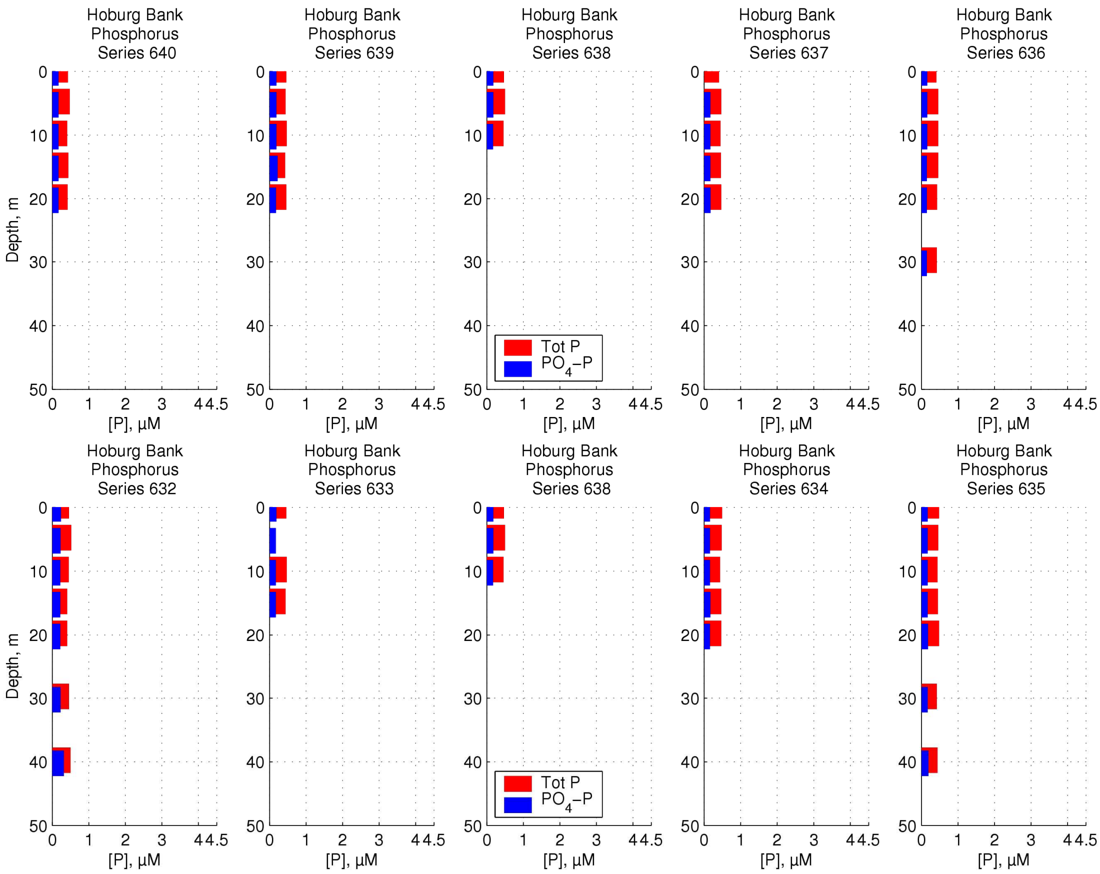


*Figure 82 Phosphorus concentrations over the Hoburg Bank*

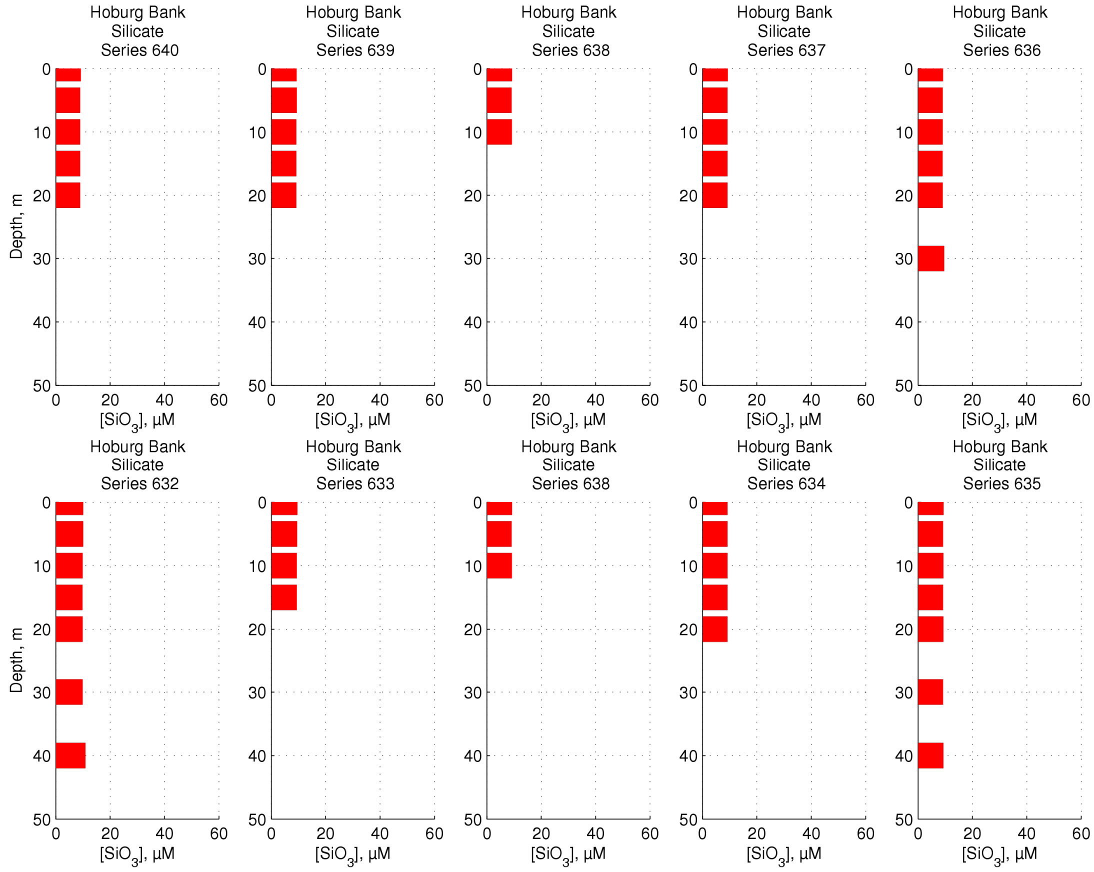


*Figure 83 Silicate concentrations over the Hoburg Bank*

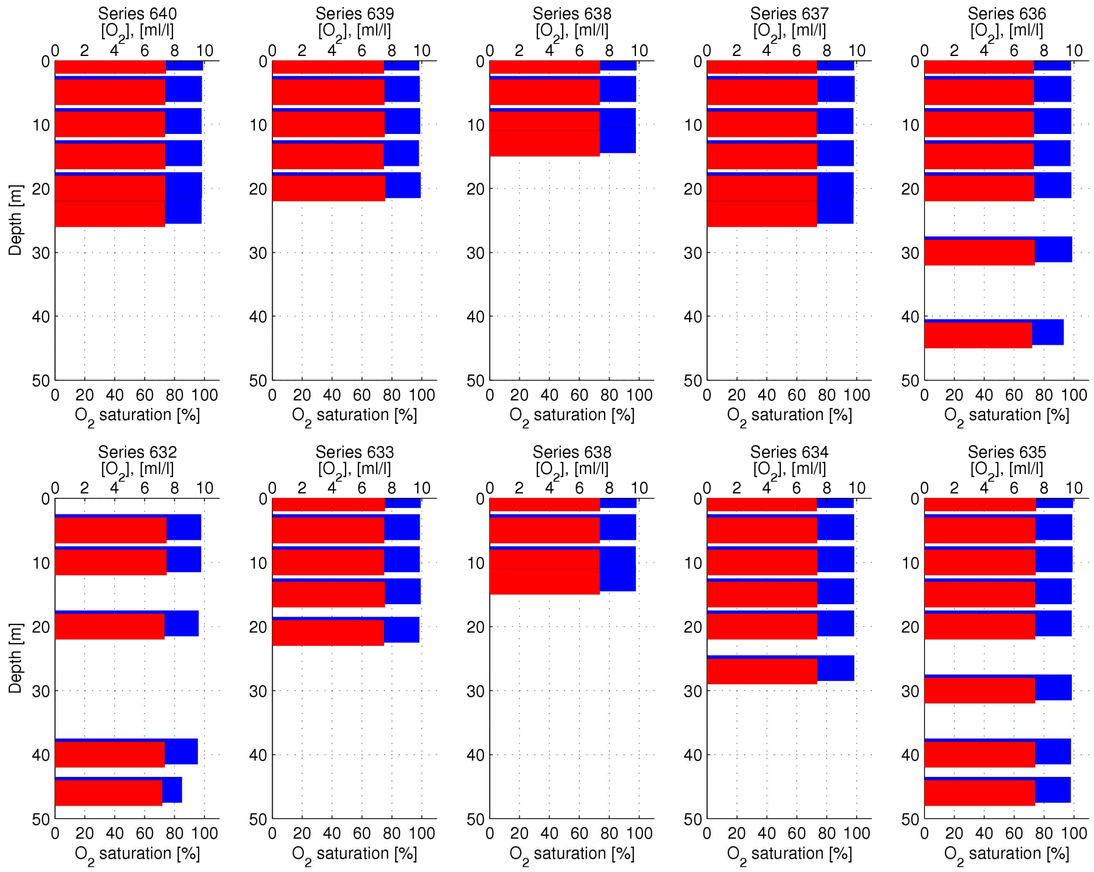


*Figure 84 Oxygen concentrations (red) and saturation (blue) over the Hoburg Bank*

## Knolls Grund

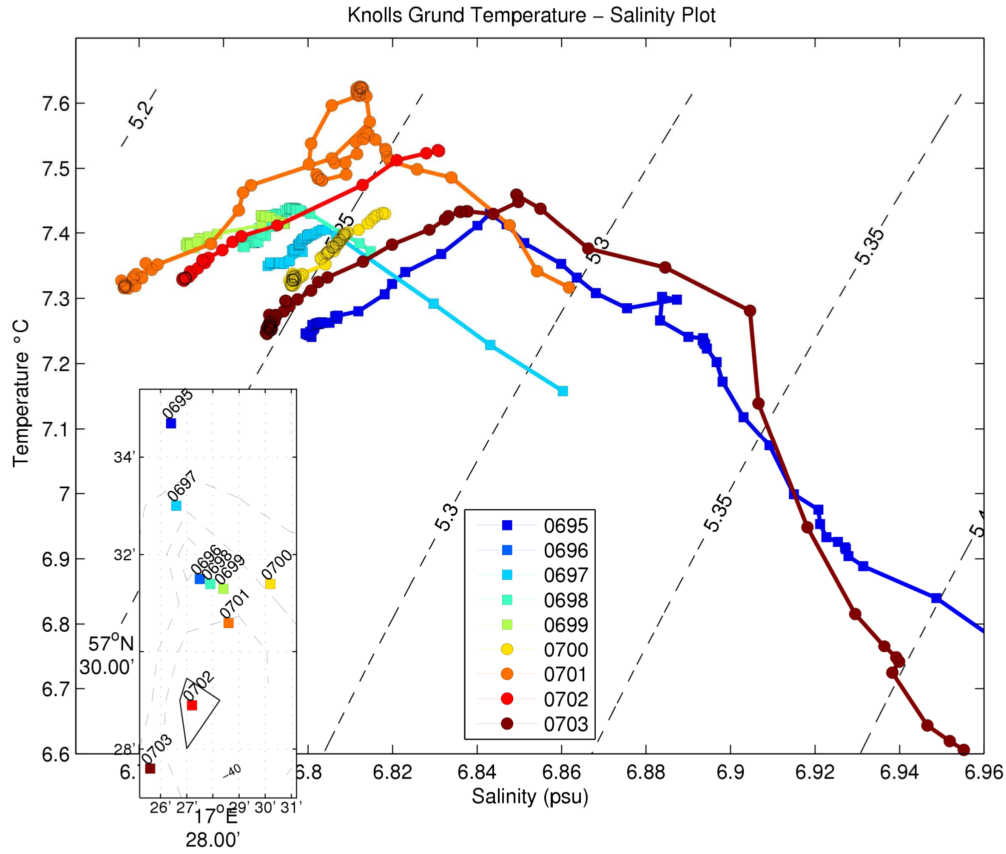


*Figure 85 Temperature – salinity plot for Knolls Grund*

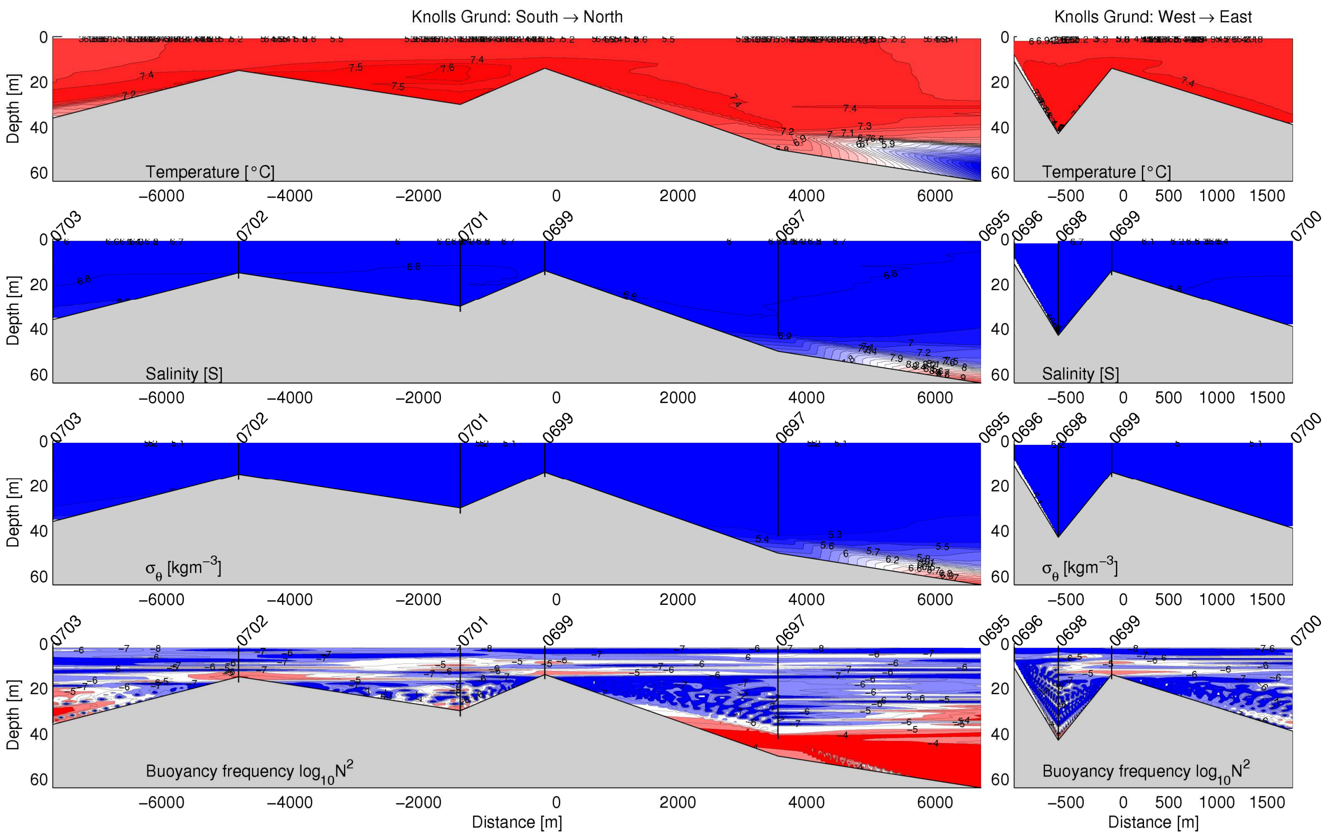


*Figure 86 Hydrographic parameters gridded across Knolls Grund*

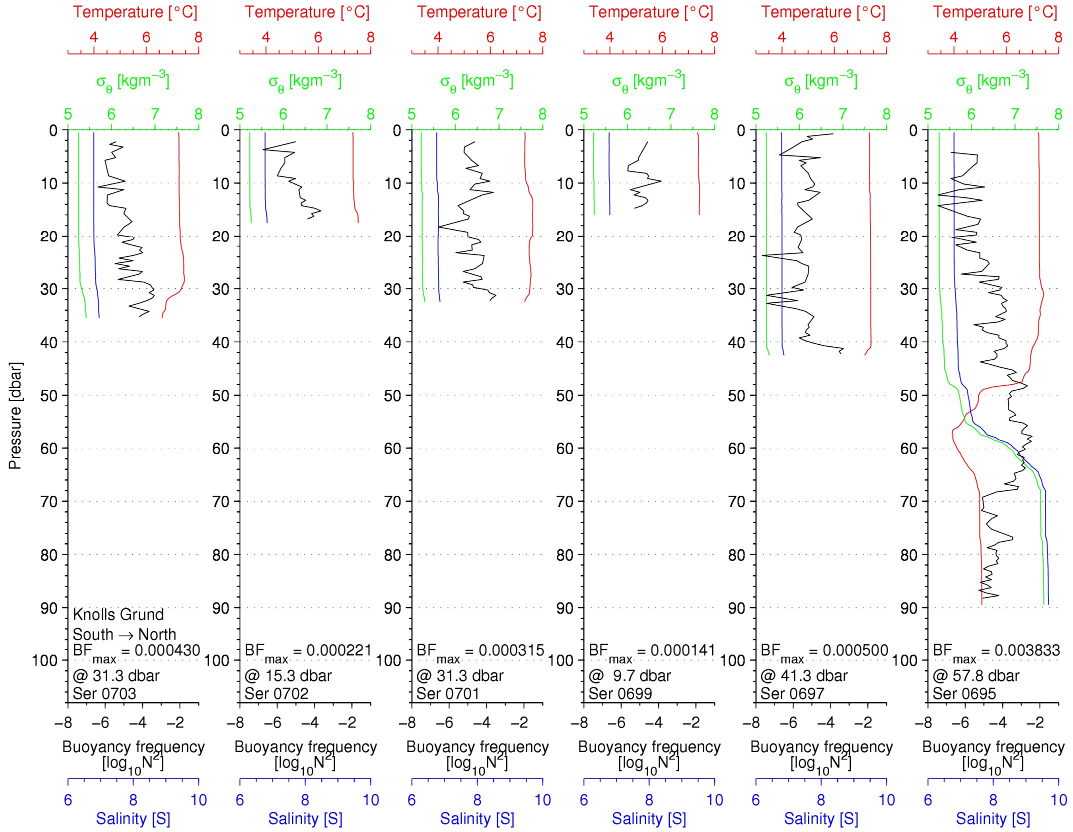


*Figure 87 CTD profiles along the south – north transect along Knolls Grund*

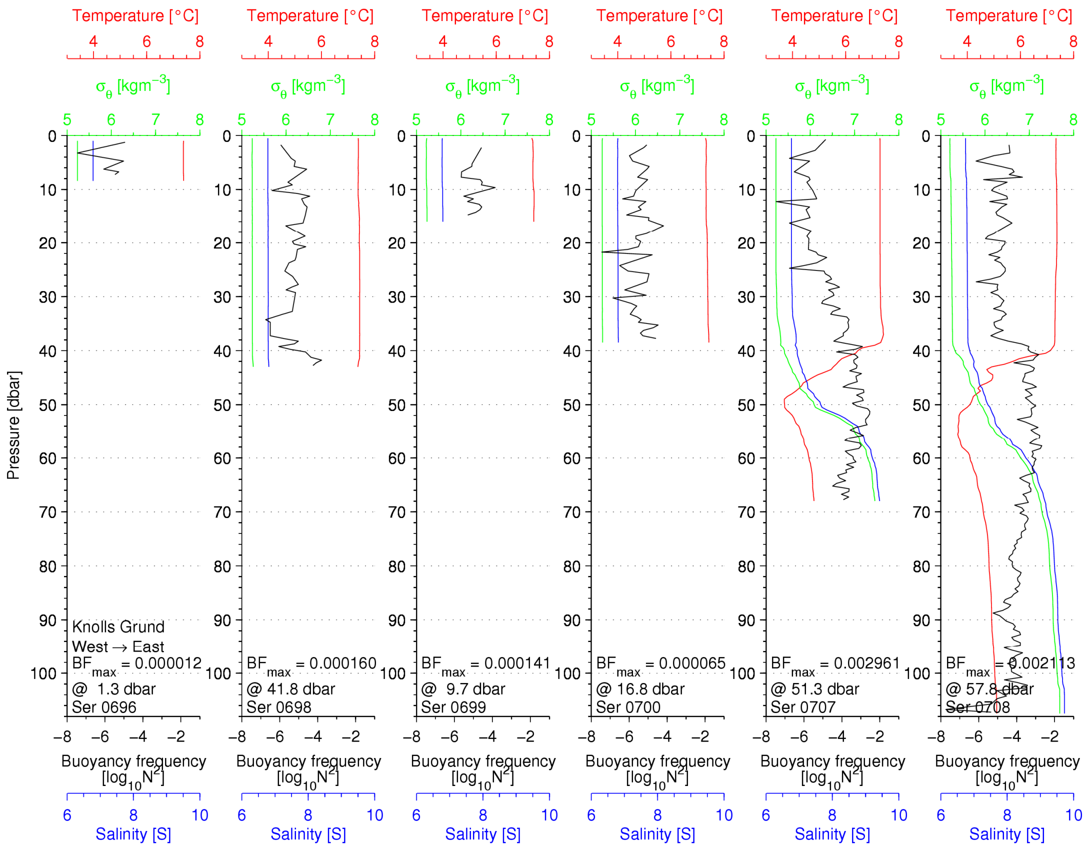


*Figure 88 CTD profiles from west – east across Knolls Grund (For comparison, profiles 0707 and 0708 show conditions further out in the West Gotland Basin)*

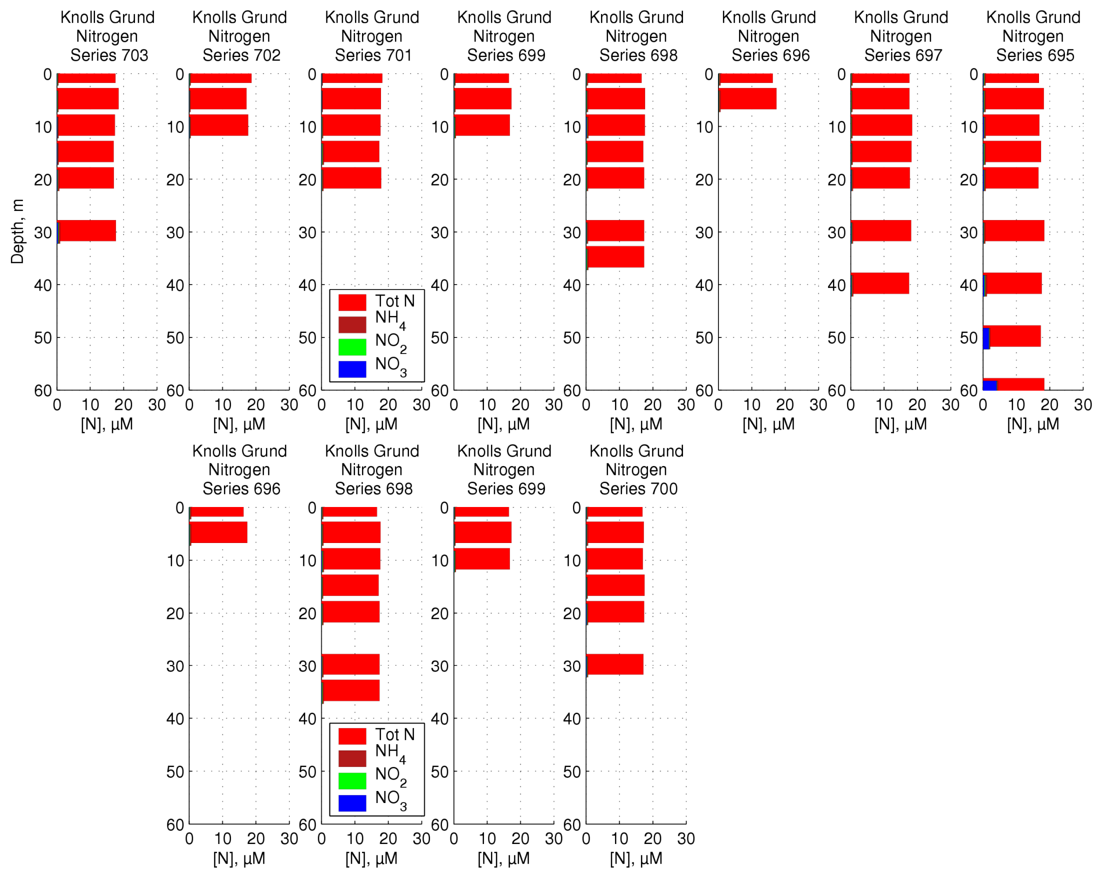


*Figure 89 Nitrogen concentrations over Knolls Grund*

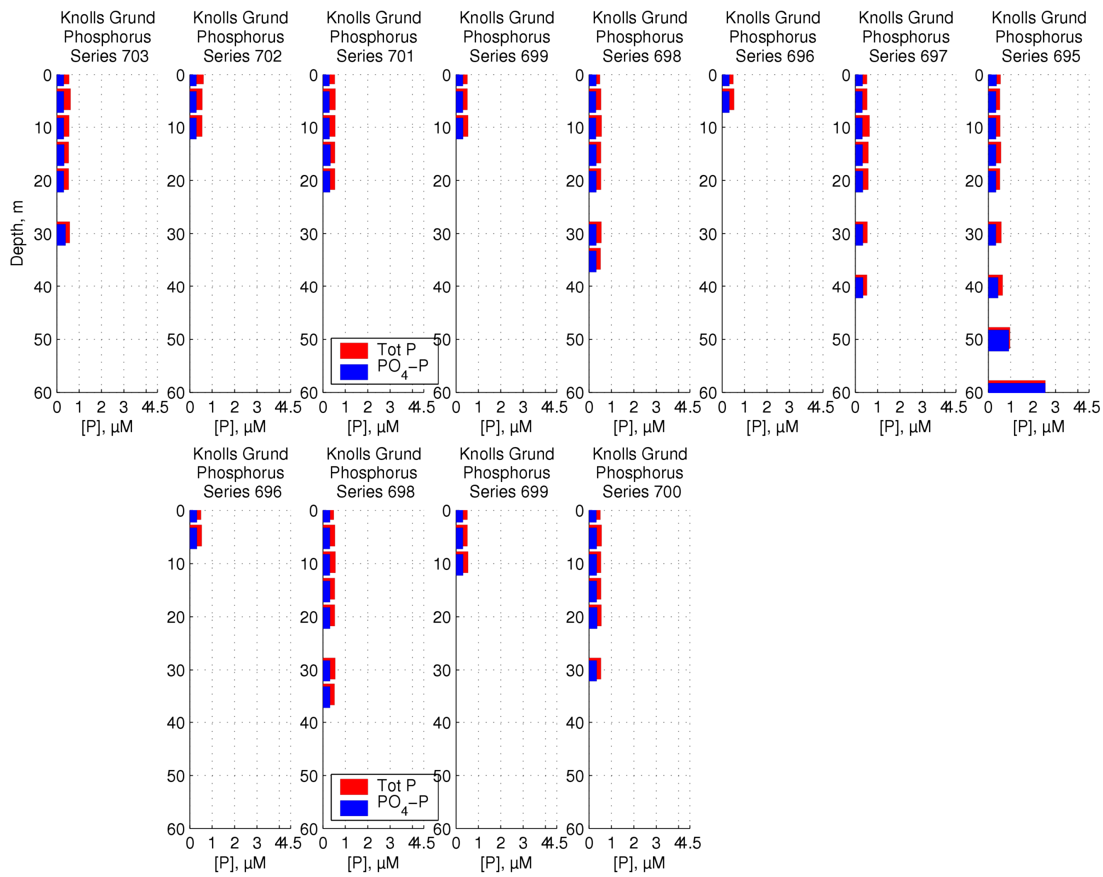


*Figure 90 Phosphorus concentrations over Knolls Grund*

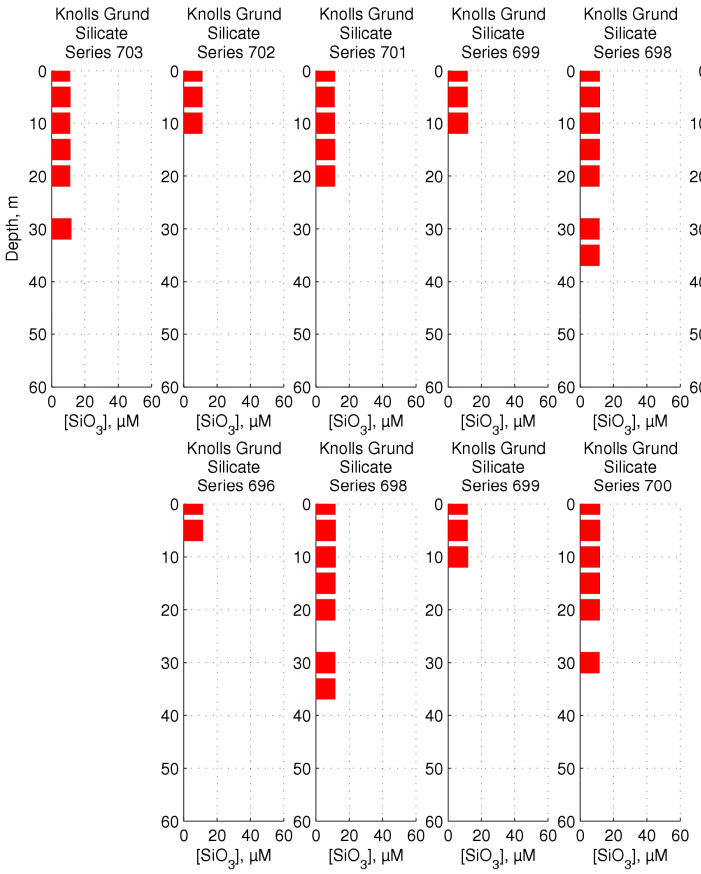


*Figure 91 Silicate concentrations over Knolls Grund*

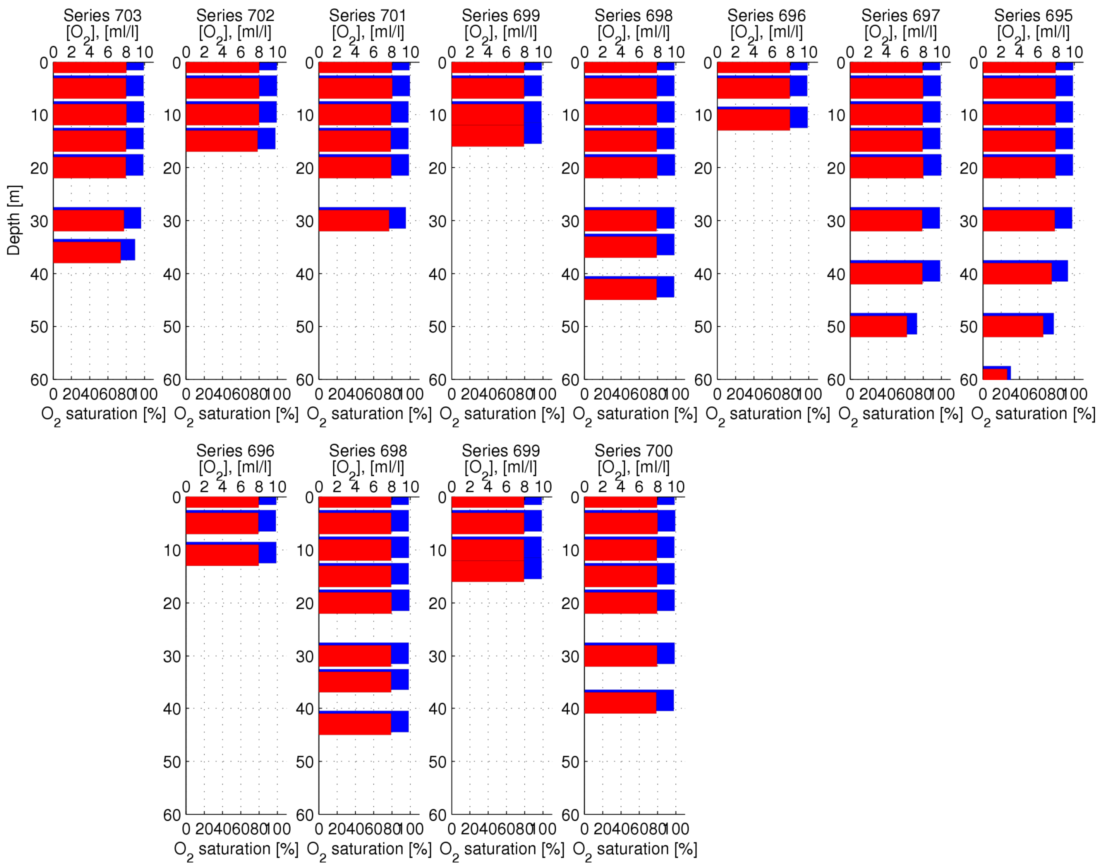


*Figure 92 Oxygen concentrations (red) and saturation (blue) over Knoll's Grund*

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