

*Variability in deep water mass properties and mixing
in the Norwegian Sea*

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Forord

Da var vi endelig her ved veis ende. Det har vært en utrolig reise som startet så tidlig som 2010. Det har vært en opplevelse uten like med mye slit og mye moro. Det at jeg skulle sitte her å skrive forord til min egen mastergrad er noe jeg ikke kunne sett for meg for 6 år siden.

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Tore Onarheim

Abstract

Decadal variations of the Norwegian Sea Deep Water are presented for the 1990s and 2000s. While salinity values have only slightly increased for the Norwegian Basin, there is a noticeable increase in potential temperature for the water below 2000 m. This is likely caused by an increase in temperature of the source waters to the region. An increasing nutrient amount was observed along with decreasing oxygen. Optimum multiparameter analysis has been used to assess the source waters of the Norwegian Sea Deep Water. Because of high nutrient values in the Norwegian Basins, results indicate that Eurasian Basin Deep Water and Greenland Sea Deep Water are not the main contributors to the Norwegian Sea. High silicate deep water from the Iceland Sea and Greenland Sea Bottom water seem more likely sources.

1. Introduction

The Nordic Seas, consisting of the Greenland, Iceland and Norwegian seas, together with the Arctic Ocean make up the Arctic Mediterranean. As relatively warm Atlantic water travels north along the coast of Norway and in to the Arctic Ocean between Svalbard and Russia it starts to lose heat to the atmosphere. As the upper layer are subjected to extensive cooling, the relatively warm salty water from the Atlantic Ocean mixed with fresher, colder Arctic Ocean, starts to transform. During winter when ice forms, brine will be released, creating dense and cold water that starts sinking towards the bottom. Following the coast of Greenland going southward, intermediate- and deep water masses produced, called overflow waters, will spread throughout the Nordic Seas, and eventually supply the North Atlantic Deep Water (Rudels et al., 1999, Rudels et al., 2005). This deep water formation process makes the Nordic Seas an important part of the Global Conveyor Belt (Broecker et al., 1991). The area has received vast attention for its importance in dense water formation and several studies of the mechanisms that create dense and overflow water has been done here (e.g Swift et al., 1981; Blindheim, 1990; Mauritzen, 1996; Rudels et al., 1999; Blindheim & Rey., 2004). However, the importance of the separate regions and water masses is not fully resolved. With climate change, the composition and volume of deep water production can change. This could affect how this area takes up CO₂, as more anthropogenic carbon is released into the atmosphere.

This thesis will provide a detailed description of changes in the deep water composition for the periods 1990-1999 and 2000-2009, in the Norwegian Sea. Along with description of changes in parameter values in the Norwegian Sea deep, an attempt to establish the sources to the deep water using optimum multiparameter analysis in this location is presented. Deep water from this region has traditionally been of large importance for overflow water leaving the North Atlantic near the Faroe-Shetland Channel, and there for its composition is important. Turrell et al. (1999) discovered that a decrease in deep water supply from the Greenland Sea resulted in a deepening of deep water

originating from the Norwegian Sea. This caused a decreased contribution from the Norwegian Sea, as less of the deep water could pass through the shallow Faroe-Shetland Channel. It is through this area that deep water from the Norwegian Sea contributes to the Iceland Scotland Overflow Water (ISOW) (Turrel et al., 1999).

1.1 Topographic description of the Nordic Seas

The Arctic Mediterranean (Figure 1) covers the oceanic area north of the Greenland-Scotland ridge to the Bering Strait, the Nordic Seas and the Arctic Ocean (Krummel, 1879). Here the Nordic Seas act as a passageway between Arctic- and the Atlantic Oceans. (Blindheim & Rey, 2004). There are several ocean basins in the Nordic Seas. The Greenland Seas has two basins, the Greenland Basin (4000m), centred on 75°N, and the much smaller Boreas Basin (3000m) to the north. The Norwegian Sea also has two basins, the Lofoten Basin (3200m), in the north, and Norwegian Basin (3600m) in the south, and these are of more similar size. The Iceland Sea is home to three basins or bathymetric constructions: The Central Icelandic Sea found to the south of the Jan Mayen Fracture Zone and west of the Jan Mayen Ridge, the west Iceland Basin that is closed off from the Central Iceland Sea by the Kolbeinsey Ridge, and the Blossville Basin, located to south western area of the entrance to the Denmark Strait. Also, worth noting is the corresponding channel in the eastern overflow area, the Faroe-Shetland Channel, that connects the Norwegian Basin and the Faroe Bank Channel.

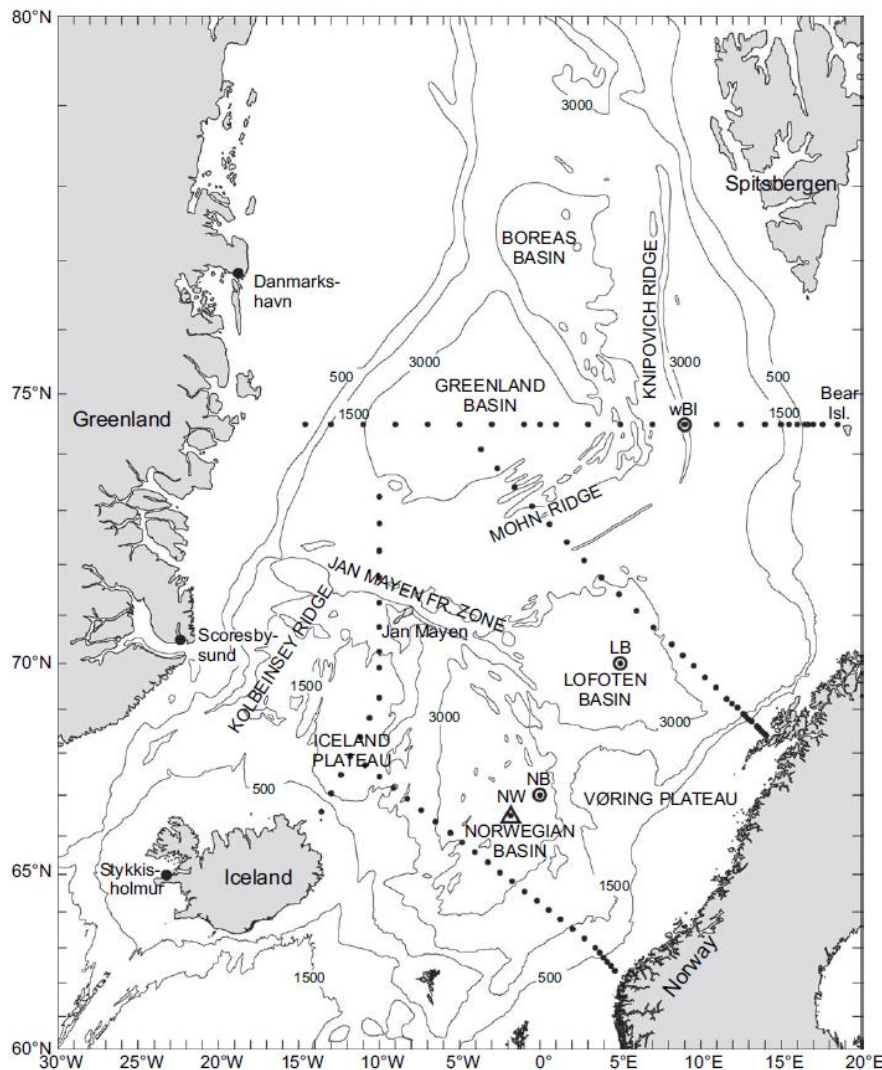


Figure 1: Bathymetric features of the Nordic Seas, adopted from Blindheim & Rey (2004).

The Nordic Seas contain a number of bathymetric features (Figure 1), as mentioned, with the mid ocean ridge (consisting of the Kolbeinsey, Mohn and Knipovich Ridges) being the most pronounced (Blindheim & Rey, 2004). This major oceanic feature cuts through the area dividing them into, a warm eastern part and a cold western one. The Jan Mayen fracture zone is another remarkable bathymetric element. On its western side, it acts as the border between the Greenland and Iceland Seas, and on the eastern side it forms the boundary between the Lofoten and Norwegian Basins.

It is not unusual to divide the Nordic Seas into oceanographic domains. These are, from east to west, -known as the Polar, the Arctic and Atlantic domains, and have different hydrographical structure. Both the Polar and Atlantic domains are named as such, due to the fact that they are directly influenced by the inflow of Polar and Atlantic Water, respectively (Swift, 1986). The Arctic domain is named after Helland-Hansen & Nansens "Arctic water", a term intended to clarify how these waters are different than those of direct and clear Polar or Atlantic origin (Swift J. H., 1986). The Arctic domain is largely dominated by internal cyclonic gyre circulation located near the central parts of the Icelandic and Greenland Seas. Here the vertical stability is much lower than in the other domains, this can result in nearly homogenous mixed layers created by mixing and cooling during winter (Swift J. H., 1986).

1.2 Circulation of the Nordic Seas

Circulation in the Nordic Seas (Figure 2) is largely governed by the bathymetry, however prevailing wind forcing has an impact in the structure of water masses and their formation (Blindheim & Rey, 2004). The western area is dominated by the East Greenland Current and its

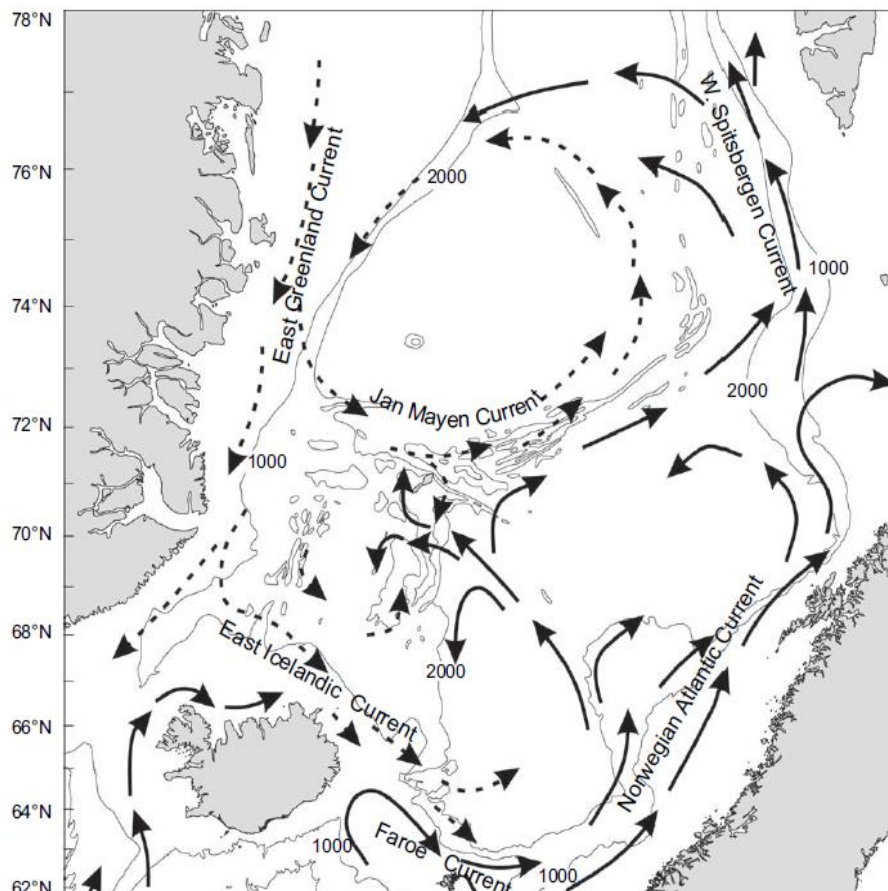


Figure 2: Illustration of the currents systems in the Nordic Seas, adopted from Blindheim & Rey (2004). Broken lines represent water coming from the Arctic Ocean, and solid lines represent water with Atlantic origin.

branches, the Jan Mayen Current and the East Icelandic Current. This follows in a cyclonic gyre, constrained by the Jan Mayen Fracture Zone, over the entire Greenland Basin. South of this, the East Icelandic Current flows along the North Icelandic slope, southwards into the Norwegian Basin. Mixing of Atlantic Water from the Faroe Current and the colder water from the East Icelandic Current occurs over the Iceland-Faroe ridge thus creating the Arctic front (Hansen & Østerhus, 2000). In the eastern part of the Nordic Seas, the upper waters are largely dominated Norwegian Atlantic Current (NAC). Further north a part of this Atlantic water re-circulates south of Spitsbergen and into the Fram Strait. When this water flows into the East Greenland Current it forms the Re-circulating Atlantic Water that occurs as an intermediate water mass. Other intermediate waters are mainly formed in the Greenland Sea by winter cooling and mixing, though some of it comes from Arctic Ocean deep water that flows into the East Greenland Current (e.g Aagaard et al., 1985; Meincke et al., 1997; Rudels et al., 1999 Rudels et al., 2002). All deep water entering the Nordic Seas from the Arctic Ocean, does so through the Fram Strait. This narrow passage allows for deep water exchange at a sill depth of 2600 m. Deep water formation in the Greenland Sea was previously thought to occur only by deep convection during winter (Nansen, 1906), but the last couple of decades have only produced intermediate water.

1.3 Dense water formation

Several processes can create dense water masses in the Nordic Seas. Perhaps the most classically regarded process is gradual densification of heat loss to the atmosphere. The huge loss of heat will in turn increase the density of the upper part of the water column, causing it to sink downward. This is the typical case of Atlantic water traveling north with the Norwegian Atlantic Current (Rudels et al., 2005). Another important process in creating dense water masses, and one especially important in the Iceland and Greenland Seas, is that of open ocean-convection (e.g Malmberg & Jönsson, 1997; Rudels et al., 2005). As mentioned earlier in the introduction, these particular areas can have a rather weak stability and experience vertical mixing during the winter season, sometimes deep into the water column (Ronski & Budëus, 2005; Rudels et al., 2005). This process could in turn potentially be important for the oceans ability to absorb anthropogenic carbon, because it transports water away from the surface and to the ocean interior (Visbeck, 2002, Jutterström & Jeansson, 2005; Jutterström et al., 2005). In order to explain the depth of the convection, both wind forcing and haline convection due to ice formation have been proposed as likely sources (Rudels, 1990; Rhein, 1991; Visbeck et al., 1995; Malmberg & Jönsson, 1997; Rudels et al., 2003; Karstensen et al., 2005;).

As of yet, there are no direct observations that deep ocean convection in the Greenland Sea ventilates the bottom water there. The levels of CFCs(chlorofluorocarbons) and other tracers have shown that sometime prior to the 1980s, water in the deepest layers have been ventilated (Karstensen et al., 2005; Visbeck & Rhein, 2000). In the late 1990s however, the convection did reach depths beneath 1400m, in turn producing a large amount of intermediate water (Karstensen et al., 2005, Ronski & Budëus, 2005).

Brine rejection from sea ice potentially causing haline convection is a third process for the creation of denser waters, particularly important for the Arctic Ocean and possibly also contributing to the deep water formation in the Greenland Sea. During the formation of sea ice, salt will be expelled from the ice to the water column below. This, along with cooling of the surface waters will increase the water density, causing the waters to sink to deeper levels. When this occurs in the regions above the shelf areas of the Arctic Ocean, this can accumulate large amounts of high-saline water, that later can be transported to the shelf break, spilling into the deeper layers along the slope (Rudels et al., 2005).

1.4 Intermediate and deep water masses in the Nordic Seas and Arctic Ocean

Arctic Ocean:

As Atlantic Water enters the Arctic Ocean via the Barents Sea, it will turn into denser water masses through several processes. These dense water masses will travel along with the East

Greenland Current, exiting the Arctic Mediterranean, mainly through the Denmark strait (Rudels et al., 1999). The intermediate and deep waters exiting the Nordic Seas resupplies up to 40% of the North Atlantic Deep Water (Rudels et al., 1999). Rudels et al., 1999 described these dense water masses as modified Atlantic Water, Canadian Basin Deep Water (CBDW), and Eurasian Deep (EBDW)- and Bottom Water (EBBW). Between the modified Atlantic Water and the CBDW, there is a decrease in temperature and an increase in salinity. This water is known as the upper Polar Deep Water (uPDW) (Rudels et al., 1999) and will be found as an intermediate water mass with salinities and temperature of 34.84 - 34.97 and -0.7 - 0.3 °C respectively (Rudels et al., 1999). In the Canadian Basin uPDW is recognized by decreasing temperatures and increasing salinities towards the deep, creating a straight stratified line in TS-plots. In the Eurasian Basin it can be recognized with a concave up profile, as a consequence of inflowing colder less saline Barents Sea branch water. CBDW has been identified in the Eurasian Basin by a salinity maximum at around 1700m and is the least dense of the deep waters of the Arctic Ocean with TS values of -1.2 - -1.0 °C, and 34.93 - 34.97 (Rudels et al., 1999). Shelf-slope convection in the Canadian Basin will redistribute heat and salt downwards through the water column, and this has been suggested to be source of the high salinity of the CBDW (Rudels et al., 1999). The EBDW is colder, denser but less saline than CBDW, and will be found underneath the CBDW with TS values of -1.4 - -1.3 °C and 34.923 (Rudels et al., 1999). The EBDW, share the shelf-slope convection characteristics of the CBDW, with constant temperature and increasing salinity with depth. As these waters travel south, they will mix with waters coming in from the Nordic Seas in the Fram Strait. These waters will follow the same path as the East Greenland Current(EGC), and the Arctic Ocean intermediate- and deep waters will exit the Fram Strait with the colder EBDW at the bottom (Olsson et al., 2005).

Greenland Sea:

The Greenland Sea intermediate- and deep waters are influenced by incoming waters from the Arctic Ocean via the EGC, the water from the Atlantic via either recirculating water from the West Spitsbergen Current or as intermediate water of the EGC, as well as local changes. Winter cooling and mixing creates a dense almost homogenous water mass, most of which is not heavy enough to create deep or bottom water. The water then sinks to intermediate levels where it can be found. This intermediate water mass is called Greenland Sea Arctic Intermediate Water (GSAIW), and is the main water mass exported from the Greenland Sea (Mauritzen, 1996). The intensity and duration of convection during winter, determines sinking depth and the volume of GSAIW produced. The uppermost deep water, between 2000-3000 m, is denoted Greenland Sea Deep Water (GSDW), and is a mixture of CBDW and EBDW from the Arctic Ocean. This water is fresher than the deep waters from the Arctic Ocean, with typical potential temperature and salinities of -0.8 - -1.3 °C, and 34.9 - 32.918 (Rudels et al., 2005), respectively, and with lower levels of oxygen than the upper layers (Blindheim & Rey, 2004). Further down the water column, there is evidence of another deep water mass, seemingly affected by earlier convection (Jeansson et al., 2008). This water mass is denoted Greenland Sea Bottom Water, and extends from 3000 m and to the ocean floor at approximately 3800m. It is less salty than the above deep water with temperature and salinities of -1.11 °C and 34.903 respectively (Jeansson et al., 2008).

Iceland Sea:

Nearly all of the East Greenland Current above 1600 m can cross over the Jan Mayen Fracture Zone and eventually into the Iceland Sea (Rudels et al., 1999). This includes fractions of uPDW, GSAIW and CBDW. The Arctic Intermediate water formed in the Iceland Sea (Iceland Sea Arctic Intermediate Water-ISAIW), is created by wintertime convection (Swift et al., 1981), and is usually found below a layer of Returning Atlantic Water(RAAW) (Rudels et al., 2005) typically around 200 m. If a winter is particularly severe these layers might diverge due to convection. Rudels et al (2005)

suggested that the densest parts of ISAIW is made up of Arctic Intermediate water formed in the Greenland Sea and that it possibly enters via the Norwegian Sea. Beneath the ISAIW, incoming uPDW and GSAIW constitutes an intermediate layer, at around 500-1000 m (Rudels et al., 1999).

Traditionally the deep water of the Iceland Sea has been thought to be similar or the same deep water found in the Norwegian Sea, with some indications that it can be more influenced by deep water from the Arctic Ocean (e.g. Buch et al., 1996; Rudels et al., 1999) near the Denmark Strait. The latter influence, along with findings of larger concentrations of CFCs and slightly higher salinity, led Fogelquist et al. (2003) to view the Iceland Sea Deep Water (ISDW) as a separate water mass. Typically found at depths greater than 1500 m, the ISDW has salinities in the area of 34.910-34.912 and temperatures $< 2^{\circ}\text{C}$.

Norwegian Sea:

The intermediate- and deep waters of the Norwegian sea are largely influenced by water coming in from the surrounding areas, no deep water formation takes place there due to the warm Atlantic Water. Arctic Intermediate Water enters the Norwegian Sea from the Iceland- and Greenland Seas (Blindheim, 1990), and is found as a wedge between the upper lying Atlantic Water and the underlying Norwegian Sea Deep Water (NSDW). It is slightly less saline than the NSDW with values between 34.87 - 34.91 (Blindheim, 1990). Bottom water from the Greenland Basin flows in through the deeper gaps of the mid ocean ridge, across a deep sill located at 2200 m in the Jan Mayen Fracture Zone (Blindheim & Rey, 2004). The water then spreads along the bottom of the Norwegian Sea (Blindheim & Rey, 2004). Previous authors (e.g. Aagaard et al., 1985; Swift & Koltermann, 1988) have named this the Norwegian Sea Deep Water, consisting mainly of a mixture between GSDW and EBDW coming in from the Arctic Ocean. Higher up in the water column, water is less constrained by bathymetry. This allows for isopycnal spreading along density levels, and thus makes it possible to form an intermediate water mass over the neighbouring Lofoten and Norwegian Basins (Blindheim & Rey, 2004). Because of the close connection that exists between the basins, property trends observed in one area can be traced back to another. However, there are some distinct features found in deep waters of the Norwegian Basins. The Lofoten Basin for example seems to be more strongly influenced by waters from the Greenland Basin (Blindheim & Rey, 2004). The differences in salinities during the 1990s noted by Blindheim & Rey in (2004) are small, but important when distinguishing between the basins. A difference in the oxygen content and nutrient (particularly silicate) concentrations was also noted during this period, and used as further evidence that the basins have different water mass structures. The Norwegian Basin typically has higher values of silicate associated with the deeper waters than the Lofoten Basin (Blindheim & Rey, 2004).

2. Data and methods

2.1 Data

All data used in this thesis was collected using the GLODAPv2 (Global Ocean Data Analysis Project version 2) data product. Only data from 1990-2013 and for the areas of interest in the Arctic Mediterranean were considered.

GLODAPv2 is a data product composed of data from 724 scientific cruises covering the global Ocean (Olsen et al., 2016). It contains biogeochemical data, that have been subjected to extensive quality control and corrected for measurement bias. The first GLODAP product, GLODAPv1.1, was

based on data collected during the WOCE/JGOFS global hydrographic survey during the 1990s, named GLODAPv1.1 (Sabine et al., 2005; Key et al., 2004). This product allowed for the first observational estimate of global ocean anthropogenic CO₂ inventory (Sabine et al., 2004). In 2009 CARINA (CARbon IN the Atlantic; Tanhua et al., 2009; Key et al., 2010) followed GLODAPv1.1, and combined biogeochemical and hydrographic data from the Atlantic, Southern and Arctic Oceans into one product. A similar collection of scientific cruise data was published in from the Pacific 2013, PACIFICA (PACific Interior Carbon) by Suzuki et al. GLODAPv2 was created in order to combine data previously collected and to create a data base that would continuously be improved.

The accuracy of the data in GLODAPv2, is believed to be better than: 0.005 for salinity, 2% for nitrate, 2% for silicate, 2% in phosphate and 1% for oxygen (Olsen et al., 2016).

The data from GLODAPv2 was extracted and prepared for use in the Nordic Seas. In order to find out which source waters make up the deep water of the Norwegian Sea, source water areas must be defined. Water masses were chosen from specific areas thought to be sources for deep water in the Norwegian Sea. These were the Arctic Ocean, the Greenland Sea and the Iceland Sea. Using MATLAB and creating ellipsoids extending outward from each of the areas assigned centre. The centres off the ellipsoid were located at: 83 °N, 6 °E and with a diameter of 125 km for the Arctic Ocean, 75 °N, 2 °W and with a diameter of 110 km for the Greenland Sea and 68 °N, 12 °W with a diameter of 110 km for the Iceland Sea. With these ramifications all data within the circles would then be used for each respective source region (Figure 3). After the data had been specified for a set area, depth profiles were constructed by simply plotting parameter data against depth, to give a visualization of the water column for the two recent decades. Intermediate water masses were included to explain the mixing from the upper layers into the deep waters, as this occurs alongside intrusions from other basins. This meant at least one deep water and one intermediate water mass from each source region (two deep waters from the central Greenland Sea). Source waters for the NSDW were chosen using the available data for each parameter, averaged over the 1990s and recent data from 2000s (only the Iceland Sea area contains values after 2009, so for this area the period is extended to 2000-13 (Tabell 1), separately. The averaged values were then assigned as water mass values for the intermediate and deep waters for the selected source regions. The deep waters were all chosen to have an upper bound of 2000 m and extending to the ocean floor, with two exceptions. For the Central Greenland Sea two deep water masses were defined, one for the depth interval 2000-3000 m, and one ≤3000 m. For the Iceland Sea, an area with a typical depth around 2500 m, the upper bound was ≤1500 m. All intermediate water masses were defined with an upper bound of 500m and extending to 1000 m. The same procedure was also done for the Lofoten- and Norwegian Basins to have a reference point for the deep and intermediate waters here, but not for use in the optimum multiparameter analysis. More detail is added regarding this procedure in the section below.

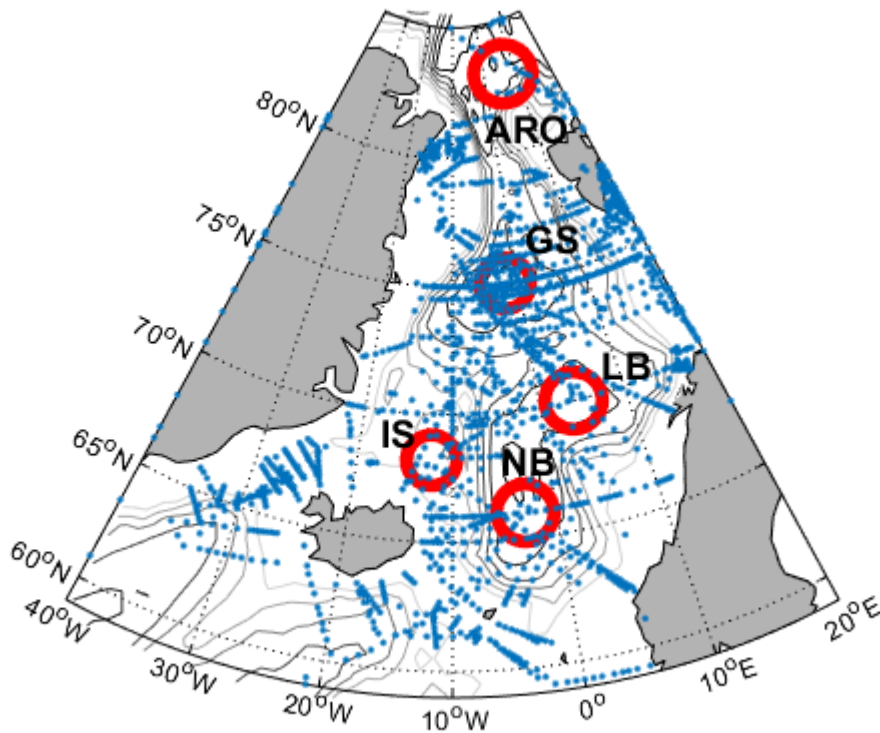


Figure 3: Map of the Nordic Seas showing stations from GLODAPv2 and defined areas used in this thesis.

Tabell 1: The number of data points collected for the Nordic Seas, split into decades and area. The points marked in the blue area are all data points found in the deeper layer >2000 m (<1500 m for the Iceland Sea).

Area	Data points (deep)	Data points (total)	Years
Norwegian Basin: 1990s	88	352	1992-97
Norwegian Basin 2000s	42	178	2002
Lofoten Basin: 1990s	58	259	1991-95,1999
Lofoten Basin :2000s	47	239	2000,2002,2009
Iceland Sea: 1990s	81	831	1991-99
Iceland Sea 2000s	116	903	2000-13
Arctic Ocean: 1990s	43	179	1991
Arctic Ocean 2000s	6	68	2002
Greenland Sea: 1990s	262	1100	1991-99
Greenland Sea: 2000s	166	756	2000,2002-2003,2005-06,2009

2.2 OMP (Optimum multiparameter) analysis

The study of water masses and mixing has traditionally been done using the often well-known relationship between temperature and salinity. The TS-diagram (Helland-Hansen, 1918) or θ S-diagram (if using potential temperature in place of in situ temperature), have been used as tools for studying mixing properties in oceanographic processes. Most notably perhaps in the works of Sverdrup et al. (1942), but also by later authors (Mamayev, 1975; Worthington, 1981). Using this type of technique, you get only limited information. As for example, one can get quantitative results from a TS-curve, through deriving the mixing triangle. This will however only result in three water

masses per water sample. For areas such as the Arctic Mediterranean, there are often more than three water masses present, and here this approach falls short. The modifications done to this method by Tomczak (1981) allowed for more water masses to be quantified at the same time. This was further improved by Mackas et al. (1987) resulting in the creation of the optimum multiparameter analysis (hereby referred to as OMP) (Tomczak & Large, 1989). The OMP method allows for accurate and comprehensive quantification of the water mass contribution to the water sample. OMP analysis has been used with success in the world oceans (e.g. Tomczak & Large, 1989; Hinrichsen & Tomczak, 1993; Poole & Tomczak, 1999), and traditionally regards the parameters as conservative. This form of OMP analysis is referred to as classical OMP and does not include changes by biogeochemical processes.

In order to perform an OMP analysis, water masses first have to be described as source water types. If a parameter is indeed a conservative one, it cannot have any sources or sinks, as is the case for temperature and salinity.

Therefore any change in their respective value must come as a result of mixing with its surrounding waters (Tomczak, 1981). The previous assumption is often true, especially when looking at smaller oceans, but is not necessarily true when regarding a larger scale. When regarding the production of water masses in the Arctic Mediterranean, more specifically in the Nordic Seas, this assumption is no longer valid. Further improvements were made to include non-conservative behaviour of nutrients and oxygen, using Redfield ratios, in order to account for this non conservative case (Karstensen & Tomczak, 1997; 1998; Poole & Tomczak, 1999). As this thesis deals with deep and intermediate water, Redfield ratios was not added.

Even though OMP uses several parameters rather than simply two, TS-plots were used as means to give a qualitative view of the general water mass situation. The use of more than two parameters result in a possibility to include several water masses in the analysis. The important distinction between water mass, water type and source water types have been defined by Tomczak (1999):

“A water mass is defined as a body of water formed in some region of the ocean, and occupies a certain volume in the ocean. A water type, on the other hand, does not exist in the physical sense as it is a mathematical description of a water mass. A water type is rather a point in a parameter space, defined by the number of parameters used. In most cases it is adequate to use one water type in order to describe a water mass, but in regions like the thermocline, one might need two. And finally, a water type describing a water mass in its source region is denoted a source water type”.

To be used in the analysis, the water masses defined (needs to be assigned a value as a sort of recognizable value. With the parameter relationships and its standard deviations, a full description of the water mass can be given. After water masses have been given specific identities, the OMP puts up a linear system of equations for a finite number of water types. The system used for the OMP analysis in this thesis is presented below:

$$\begin{aligned}
 x_1T_1 + x_2T_2 + x_3T_3 + x_4T_4 + x_5T_5 + x_6T_6 &= T_{obs} + R_T \\
 x_1S_1 + x_2S_2 + x_3S_3 + x_4S_4 + x_5S_5 + x_6S_6 &= S_{obs} + R_S \\
 x_1Ox_1 + x_2Ox_2 + x_3Ox_3 + x_4Ox_4 + x_5Ox_5 + x_6Ox_6 &= Ox_{obs} + R_{Ox} \\
 x_1Ph_1 + x_2Ph_2 + x_3Ph_3 + x_4Ph_4 + x_5Ph_5 + x_6Ph_6 &= Ph_{obs} + R_{Ph} \\
 x_1Ni_1 + x_2Ni_2 + x_3Ni_3 + x_4Ni_4 + x_5Ni_5 + x_6Ni_6 &= Ni_{obs} + R_{Ni} \\
 x_1Si_1 + x_2Si_2 + x_3Si_3 + x_4Si_4 + x_5Si_5 + x_6Si_6 &= Si_{obs} + R_{Si} \\
 x_1 + x_2 + x_3 + x_4 + x_5 + x_6 &= 1 + R_{MC}
 \end{aligned}$$

Here T_i , S_i , Ox_i , Ph_i , Ni_i and Si_i represent the parameter indexes in the water type (temperature, salinity, oxygen, phosphate, nitrate and silicate respectively), and where i represents the water type. T_{obs} , S_{obs} , Ox_{obs} , Ph_{obs} , Ni_{obs} and Si_{obs} represent the observed values from the water

sample and R represents the residual of each parameter. The last line represents that the sum of all the contributions must be in unity, that the entire mass must be conserved. The entire system is then solved by minimizing the residual of fit, and introduction a requirement that no relative contribution can be negative. The system is often projected by the following equation:

$$Gx - d = R$$

G is a matrix containing all parameter values for the different water types (the source water matrix), x is a vector that gives the relative contributions of a source water to the sample being analysed, d is a vector containing the measured parameter values of a water sample, and R is the residual vector. All parameters have to be normalized and weighted before the analysis can continue and this following the procedure of Tomczak & Large (1989). It is important to do this normalisation in order to be able to compare the parameters of different units. Means, and standard deviations, were calculated for all water masses in their source region over the two time periods mentioned above, and variances were calculated from these. Weights were calculated using the equation first described by Tomczak & Large (1989):

$$W_j = \frac{\sigma_j^2}{\delta_{jmax}}$$

Here σ_j^2 represents the ability of parameter j to resolve differences in the water mass content while δ_{jmax} is the largest variance associated with the parameter j . σ_j was calculated from the source waters standard deviations and δ_{jmax} was found by taking the largest variance from the produced source water matrix. To obtain weights for each decade and area, variances were calculated first for each area, then for the source water matrix. To get the most accurate values, the weights only included the water masses used in the OMP analysis.

The source water matrix was created based on data in the source water regions. This was done for the periods 1990-1999 (Table 2) and 2000-2009 (Table 3) (for the Iceland Sea this extends to 2013 to include the most recent data). Using property-property plots (in particularly 3 relationships: temperature-salinity, salinity-silicate and salinity-oxygen), the water masses with the closest relation to the parameters of the Norwegian Basins were chosen for later use in the OMP analysis. These plots only included collected data for the deeper layers of Norwegian- and Lofoten Basins, and were split into decades. Regular testing using mentioned methods was done to check if the source water types chosen were accurate and logical representations of the water composition in the deeper layers. The analysis was run with 2000 m being the upper bound as well as the density being set at σ_θ 28.06 kg/m³. Six parameters were used in the analysis along with mass conservation: Salinity, potential temperature, oxygen, phosphate, nitrate and silicate. As this study only used six variables at one time, only six water masses were available for use during the analysis

Table 2: Properties of Source Waters -1990-99

Source Waters	Salinity	Pot.-temp °C	Density kg/m^3	Phosphate $\mu mol/kg$	Nitrate $\mu mol/kg$	Silicate $\mu mol/kg$	Oxygen $\mu mol/kg$
GSDW	34.904	-1.08	28.079	0.99	14.58	11.00	304
GSBW	34.901	-1.17	28.080	0.99	14.60	11.67	306
GSAIW	34.879	-0.87	28.050	0.92	13.34	7.37	323
ISDW	34.911	-0.95	28.079	0.98	14.65	12.10	296
dISIW	34.905	-0.57	28.058	0.93	13.97	8.75	300
NSBW-NB	34.909	-1.03	28.081	1.00	15.13	13.21	293
NSBW-LB	34.909	-1.03	28.081	1.01	15.18	13.11	296
AODW	34.932	-0.93	28.096	0.97	14.81	11.04	300
AOIW	34.916	-0.57	28.067	0.93	14.09	9.12	302
Weights-NB	32.7	11.1		6.5	10.6	50.2	15.3
Weights-LB	32.7	11.1		5.3	10.4	49.2	14.9

Abbreviations of water masses are: AODW- Arctic Ocean Deep Water, AOIW- Arctic Ocean Intermediate Water, dISIW- dense Iceland Sea Intermediate Water, GSAIW-Greenland Sea Arctic Intermediate Water, GSBW-Greenland Sea Bottom Water, GSDW-Greenland Sea Deep Water, ISDW- Iceland Sea Deep Water, NSBW-LB/NB- Norwegian Sea Bottom Water- Lofoten/Norwegian Basin. Separate weights calculated for each basin.

Table 3: Properties of Source Waters-2000-2009¹

Source Waters	Salinity	Pot.-temp °C	Density kg/m^3	Phosphate $\mu mol/kg$	Nitrate $\mu mol/kg$	Silicate $\mu mol/kg$	Oxygen $\mu mol/kg$
GSDW	34.909	-0.98	28.079	1.00	14.73	11.40	301
GSBW	34.906	-1.08	28.080	1.00	14.80	12.10	303
GSAIW	34.889	-0.77	28.053	0.88	12.92	6.64	329
ISDW	34.912	-0.88	28.077	0.99	14.85	12.54	296
dISIW	34.901	-0.54	28.053	0.93	14.00	8.33	304
NSBW-NB	34.910	-1.01	28.081	1.02	15.44	13.39	296
NSBW-LB	34.910	-0.97	28.079	1.02	15.15	13.3	295
AODW	34.924	-0.90	28.088	0.97	14.76	11.08	301
AOIW	34.902	-0.60	28.056	0.93	14.16	8.50	308
Weights-NB	4.4	14.2		8.8	17.7	50.0	65.9
Weights-LB	4.4	12.9		8.2	15.20	41.5	69.9

Abbreviations of water masses are: AODW- Arctic Ocean Deep Water, AOIW- Arctic Ocean Intermediate Water, dISIW- dense Iceland Sea Intermediate Water, GSAIW-Greenland Sea Arctic Intermediate Water, GSBW-Greenland Sea Bottom Water, GSDW-Greenland Sea Deep Water, ISDW- Iceland Sea Deep Water, NSBW-LB/NB- Norwegian Sea Bottom Water- Lofoten/Norwegian Basin. Separate weights calculated for each of the Norwegian basins.

¹Years included beyond 2009 (extends to 2013) only occur in the Iceland Sea, and only affect ISAIW, and ISDW.

The procedure meant that four separate weights were used in the OMP-analysis, each calculated from the six water masses used in the appropriate basin. As the water masses were exclusively selected from the deeper parts of the Nordic Seas, the weights appeared lower than what is usual for this sort of analysis. The small spread of deep water salinities and temperature, produced particularly low weights for these key parameters, especially for the 2000s (see Table 3). While oxygen and silicate arose as variables with much higher weights than previously presumed.

A problem with the residual of fit of the mass conservation quickly arose following this, as no combination of known water masses produced an analysis with an acceptable fit. Even when using water masses created from the targeted basins the residuals proved too high for a “good fit”. A good fit is any analysis run that provides a mass conservation residual of fit $\leq 5\%$. This means that the included source waters cannot fully explain the analysed data. This indicates that the definition of the water masses is not good enough, or that the definitions are outdated. A thorough look at parameter distribution vs depth for each of the basins and for each decade visualized the problem. Particularly high values of silicate, nitrate and low values of oxygen in the deep water of the Norwegian Sea, seemed responsible. As an answer to this, water masses based on these extreme values were produced in order to act as an upper bound for the mentioned values as well as the remaining ones (see section below).

2.3 Source waters

Intermediate and Deep waters were assigned using averages from each source water area. Below, the different source waters are presented with average value for each decade. All averaged values are found in Table 2 and 3.

Arctic Ocean:

For the area selected in the Arctic Ocean, an intermediate water mass between 500-1000 m was assigned, and was denoted Arctic Ocean Intermediate Water (AOIW). To represent the deep water of this region, a water mass from 2000m and to the ocean floor around 4000 m was chosen. It is important to note that not much data is available for this area, and that the only two years on record are 1991 and 2002 (Figure 4). AOIW became less saline and warmer from 1991 to 2002 respectively. Oxygen and nitrate increased, while the silicate content decreased. The AODW showed similar changes and decreased in salinity and increased in temperature. Nutrient values here had a decrease in nitrate while silicate increased. In both the intermediate layer and the deep layer the phosphate values remained around one value ($0.93 \mu\text{mol/kg}$ for AOIW and $0.97 \mu\text{mol/kg}$ for AODW) for both years. Oxygen increased from 1991 to 2002. From figure 7 it is possible to see that the deep water values of the Arctic Ocean are saltier (a), warmer (b) and contain less nutrients(d,e,f) then the Norwegian Sea. It also has slightly more oxygen in the deeper layers (c).

Greenland Sea:

Using source waters mentioned previously in the introduction, three source waters from the Greenland Sea for used in the OMP analysis. The GSAIW, with depth range of 500-1000 m, was used for the intermediate layer. This was not only for the possibility of mixing with deeper layers locally, but also in the Norwegian Sea. Blindheim (1990) suggested for example that GSAIW was one of the sources for NSAIW. As can be seen in Table 2 and 3 the GSAIW experienced an increase salinity, temperature and oxygen from the 1990s to the 2000s, however nutrient content decreases. The GSDW, located between 2000-3000 m and the GSBW, located from 3000 m to around 3800 m also became saltier and warmer, but its oxygen levels decreased. Another apparent difference from the evolution in GSAIW, nutrient in the deeper layer, both for GSDW and GSBW, increase (Table 2,3). Figure 5 shows two typical years for the Greenland Basin, one from each decade, and how it differs from the deep water from the Norwegian Sea. In general, the Greenland Sea deep waters for these two years, are less salty, colder and contain more oxygen than what the Norwegian Sea does. GSDW and GSBW also contain less nutrients than what is true for the deep waters of the Norwegian Sea (Figure 5 d,e,f)

Iceland Sea:

Because of the shallow depth that ISAIW is located at, it was not thought to have any large impact on the deeper layer. Instead an intermediate layer between 500-1000 m was chosen, the water named dense Iceland Sea Intermediate Water (dISIW). As witnessed for the Greenland Sea, salinity decreased from the 1990s to the start of the 2010s while temperature increased (Table 2,3). Oxygen increased along with nitrate and phosphate, while silicate values decreased. ISDW is located between 1500 and approximately 2000 m. During the same time period salinity only increased by 0.001, but temperatures increased by 0.7 °C. All of the nutrients increased while oxygen remained the same (Table 2,3). Figure 6 shows how the years 1991 and 2003 differ from the deep water data point of the Norwegian Sea. Through this figure it is easy to see how much shallower the Iceland Sea is. Another interesting observation is how the deeper layer of the Norwegian Sea, seems like an extension of the ISDW.

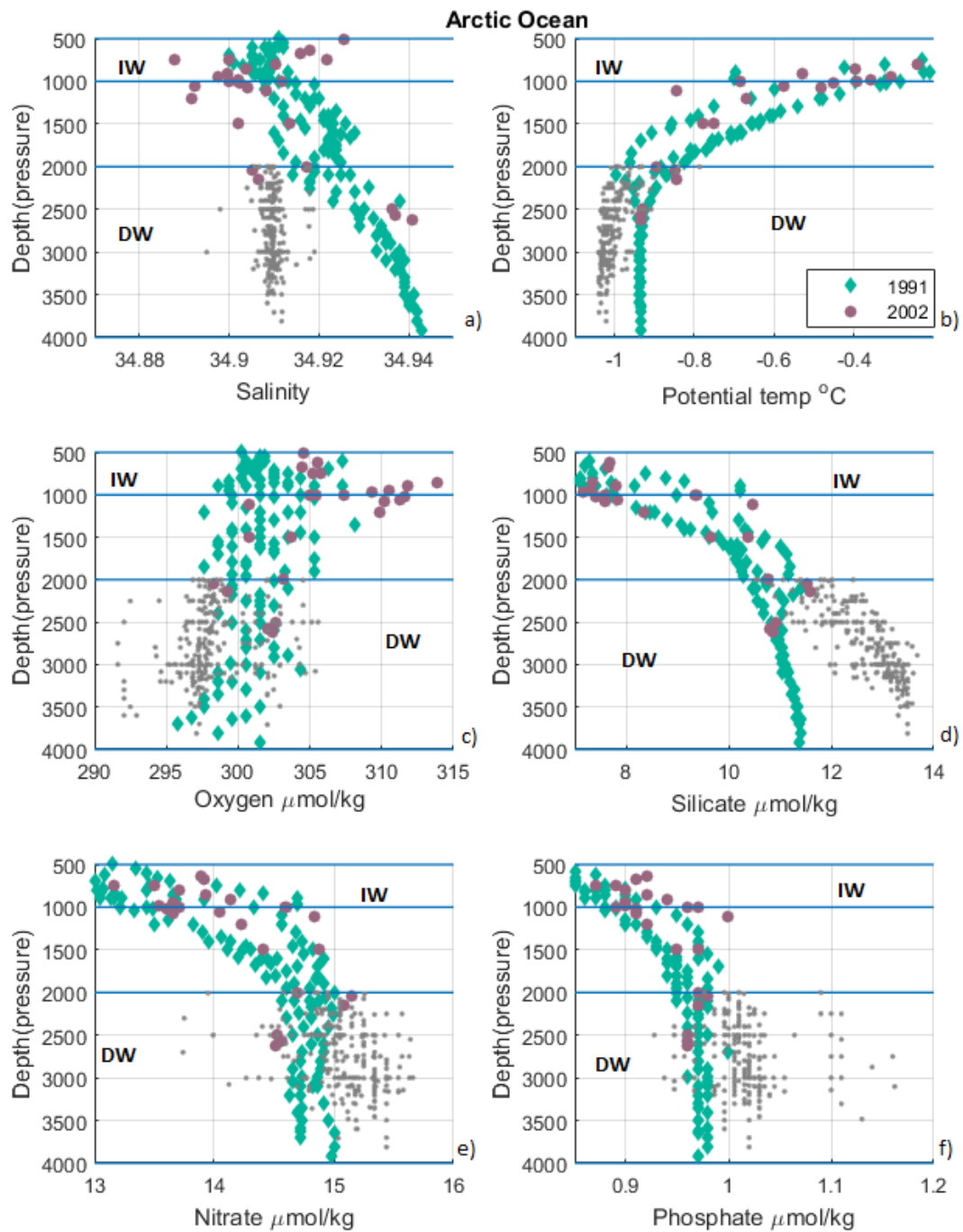


Figure 4: Depth profile of the Arctic Ocean for the years 1991 and 2002. The grey dots are all data points from the Norwegian Sea, thus only located below 2000m. The two layers, 500-1000m and 2000-4000m represent where intermediate water (IW) and deep water (DW) are selected from. a) Salinity, b) potential temperature, c) oxygen, d) silicate, e) Nitrate, f) phosphate.

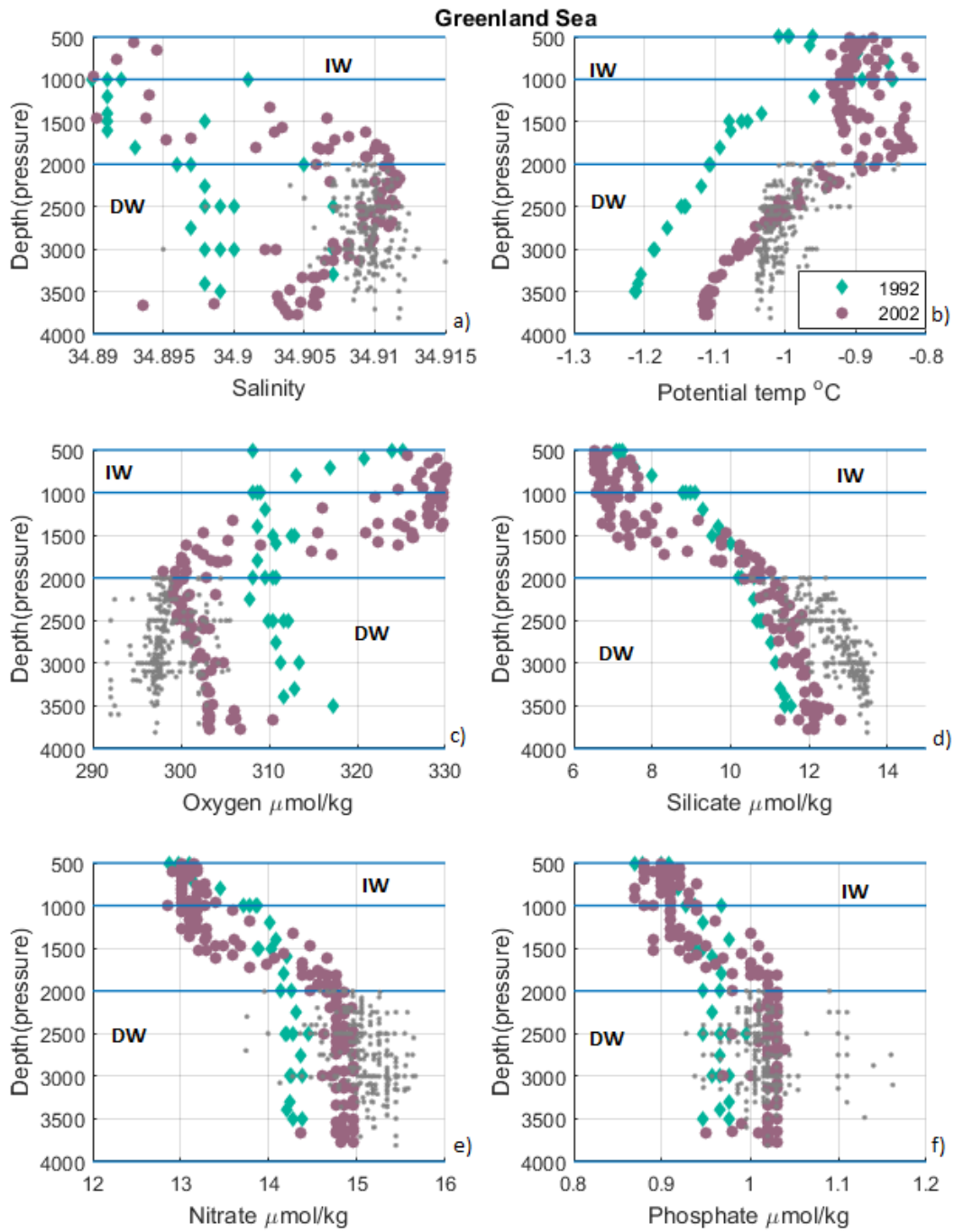


Figure 5: Depth profile of the Greenland Sea for the years 1992 and 2002. The grey dots are all data points from the Norwegian Sea, thus only located below 2000m. The two layers, 500-1000m and 2000-4000m represent where intermediate water (IW) and deep water (DW) are selected from. a) Salinity, b) potential temperature, c) oxygen, d) silicate, e) Nitrate, f) phosphate.

Norwegian Sea:

The deep waters in the Norwegian Basins contained some rather unconventional variable values, compared with the surrounding basins. Both the Lofoten- and Norwegian Basins contained large nutrient values in the deeper layers, unmatched with the surrounding basins, the closest is perhaps the Iceland Sea. This was combined with rather low oxygen values, at least for the Norwegian basin. During the 1990s a large portion of the silicate values in the Norwegian Basin were above 13 $\mu\text{mol/kg}$ and most above 12 $\mu\text{mol/kg}$. Compared to the Greenland basin in particular, this was very high and even when put against the values from the Icelandic Sea, the values are large. Because of this mismatch in parameter values, two deep waters, one for each of the Norwegian Basins, were added. These were constructed based on highest nutrient values in the basins, and with the smallest of the oxygen values. This deep water constructed on extreme values was named Norwegian Basin Bottom Water, as most of the large values were connected with depth. In Tables 2,3 the notations NB and LB denote if the deep water is associated with the Norwegian- or the Lofoten Basin. Figures 7 and 8 show two typical years for the Norwegian Sea, plotten with deep water data from the same area.

Figure 9 shows the distribution of all data collected in the Norwegian Basin during the period 1992-97 and the individual year 2002, below 2000 m. Figure 10 shows a similar picture, but for the Lofoten Basin for the 1990s and three years of the 2000s: 2000, 2002 and 2009. Potential temperature, silicate, oxygen and nitrate were plotted against salinity in order show that the source waters in Nordic Seas cannot entirely account for the low oxygen and high nutrients found here. Ideally the source waters would surround the data, in order to be able to explain them. For potential temperature, this seems true, in both basins. However, when looking at the nutrients nitrogen and silicate and oxygen it seems that traditional source water values cannot account for the result. An upper bound seems to be missing from both basins, and the "box" cannot be completed. The same can be said for a lower bound when speaking of oxygen, and it seems that it would take a source water with silicate values around 14-15 $\mu\text{mol/kg}$, nitrate values around 16 $\mu\text{mol/kg}$ and oxygen values as low as 290. This is not seen in the Nordic Seas. AOIW and GSDW were not included in the figures nor were they included in the OMP analysis. With the problem of only being able to include six source waters in the analysis, these were excluded as they were not close enough in value, based on figures similar to 9 and 10

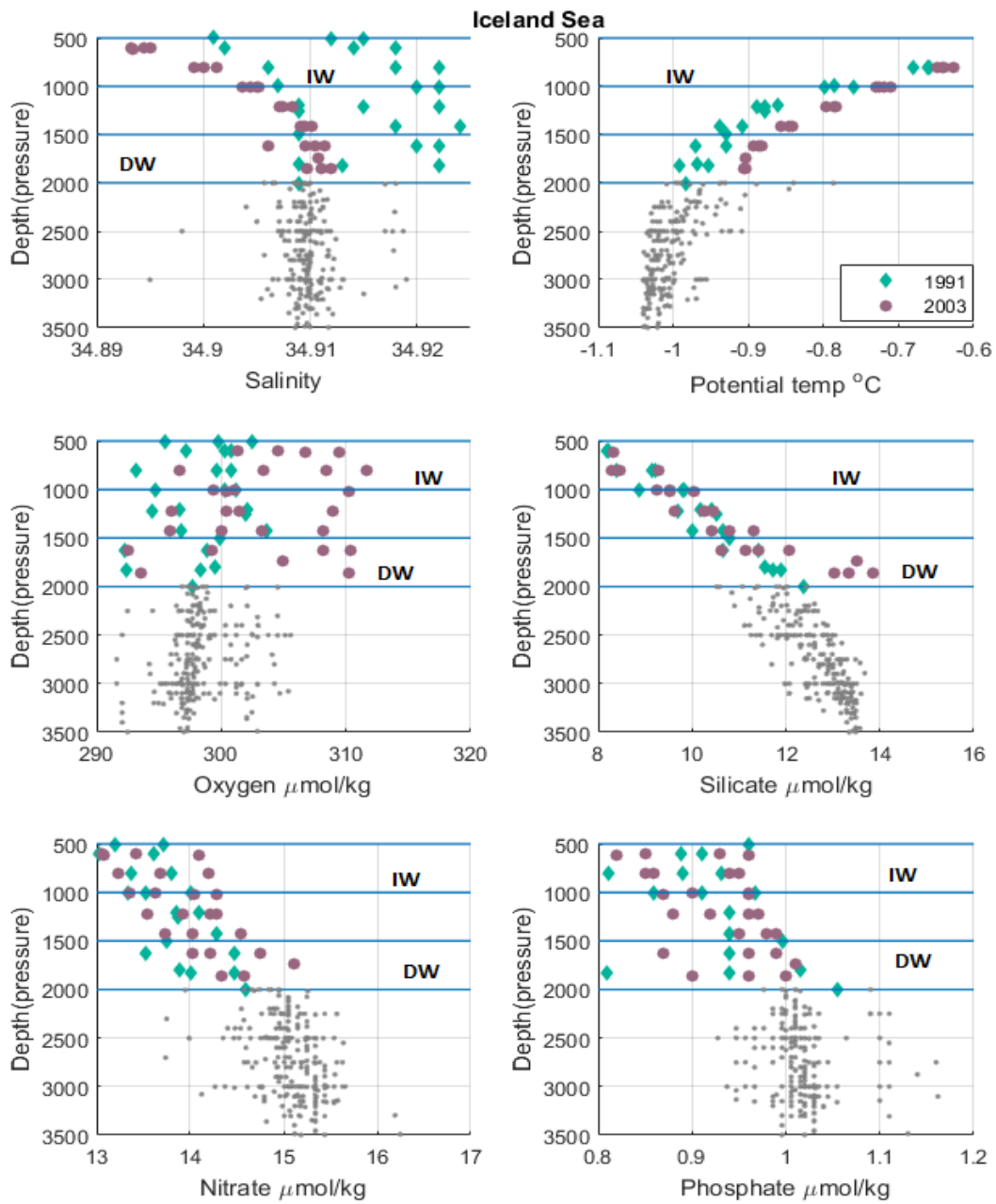


Figure 6: Depth profile of the Iceland Sea for the years 1992 and 2002. The grey dots are all data points from the Norwegian Sea, thus only located below 2000m. The two layers, 500-1000m and 2000-4000m represent where intermediate water (IW) and deep water (DW) are selected from. a) Salinity, b) potential temperature, c) oxygen, d) silicate, e) Nitrate, f) phosphate.

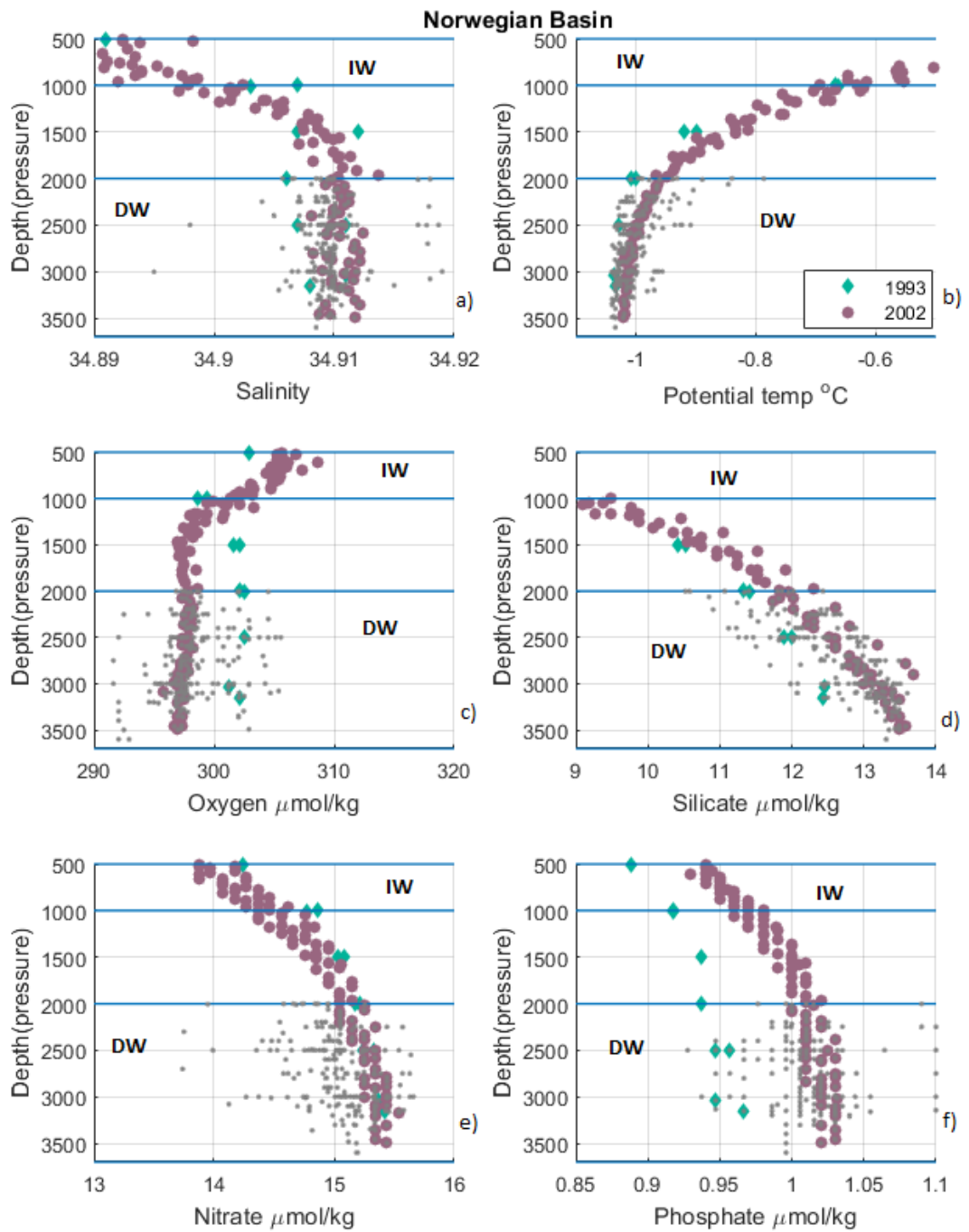


Figure 7: Depth profile of the Iceland Sea for the years 1992 and 2002. The grey dots are all data points from the Norwegian Sea, thus only located below 2000m. The two layers, 500-1000m and 2000-4000m represent where intermediate water (IW) and deep water (DW) are selected from. a) Salinity, b) potential temperature, c) oxygen, d) silicate, e) Nitrate, f) phosphate.

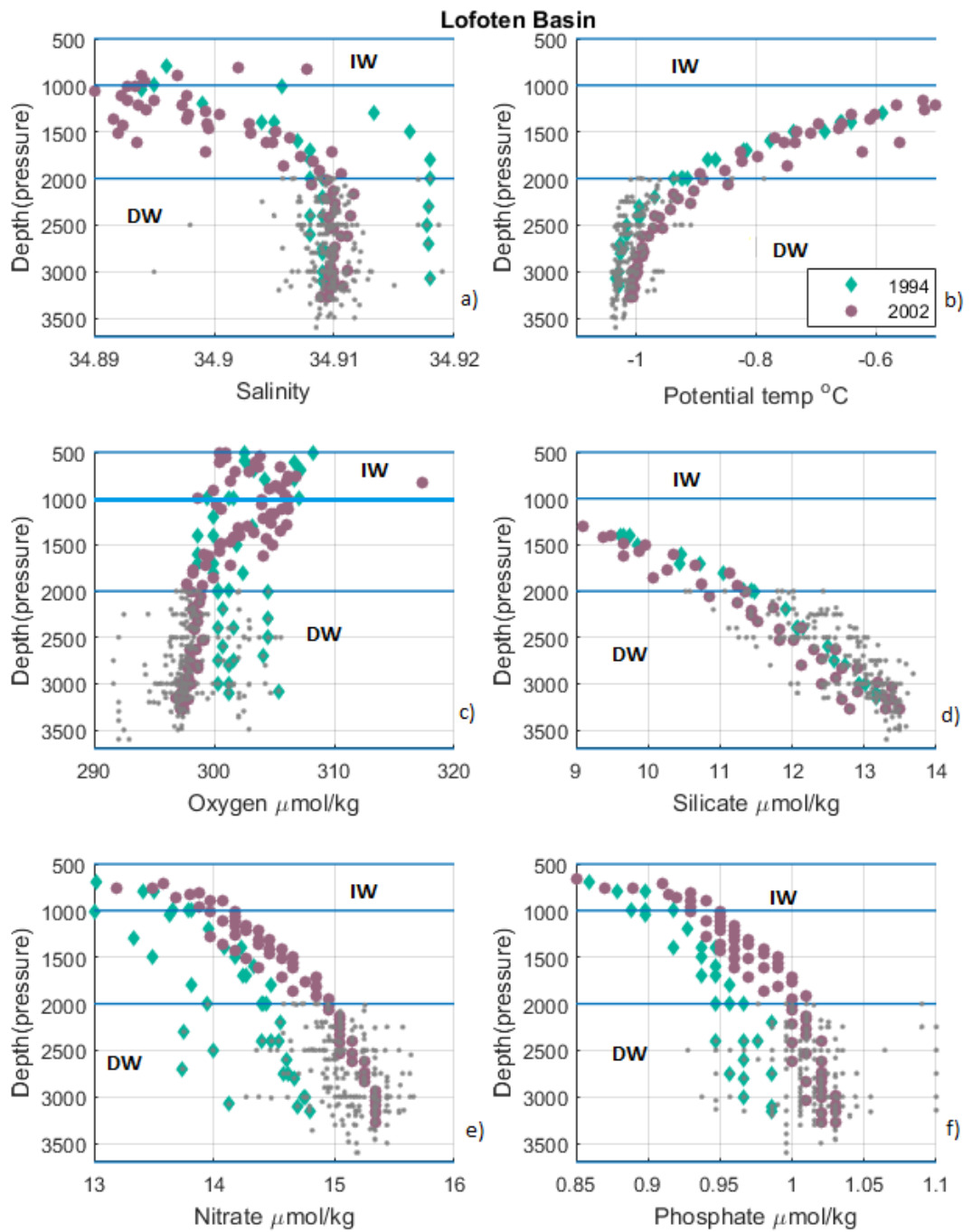


Figure 8: Depth profile of the Iceland Sea for the years 1992 and 2002. The grey dots are all data points from the Norwegian Sea, thus only located below 2000m. The two layers, 500-1000m and 2000-4000m represent where intermediate water (IW) and deep water (DW) are selected from. a) Salinity, b) potential temperature, c) oxygen, d) silicate, e) Nitrate, f) phosphate.

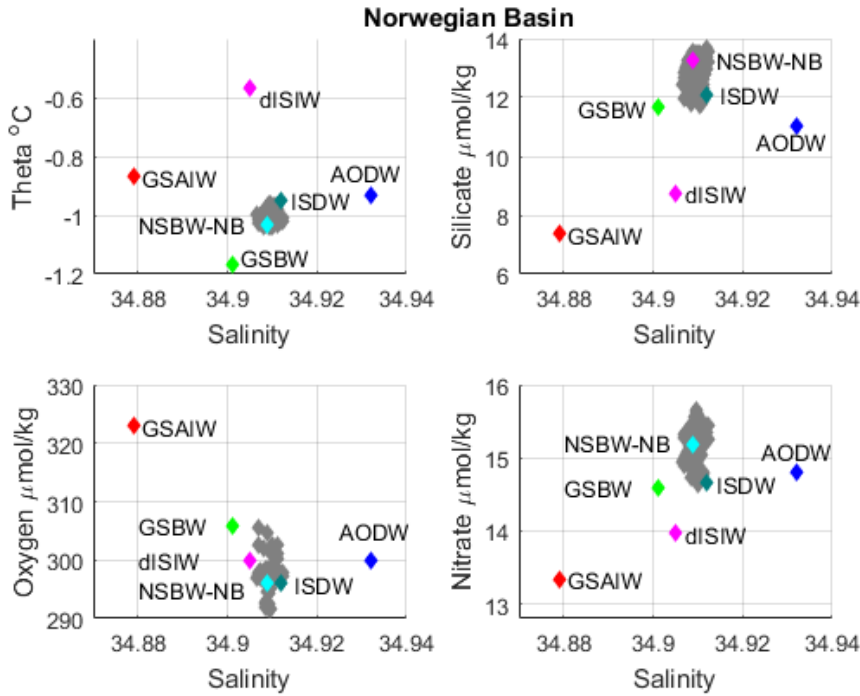


Figure 9: Potential temperature, oxygen and nutrients as functions of salinity for the Norwegian Basin, restricted for the time periode 90-99 and for depth>2000m. Grey dots represent deep water data, coloured dots represent source waters. NSBW-NB- Norwegian Sea Bottom Water-Norwegian Basin, GSAIW-Greenland Sea Arctic Intermediate Water, dISIW- dense Iceland Sea Intermediate Water, GSBW-Greenland Sea Bottom Water, ISDW- Iceland Sea Deep Water, AODW- Arctic Ocean Deep Water.

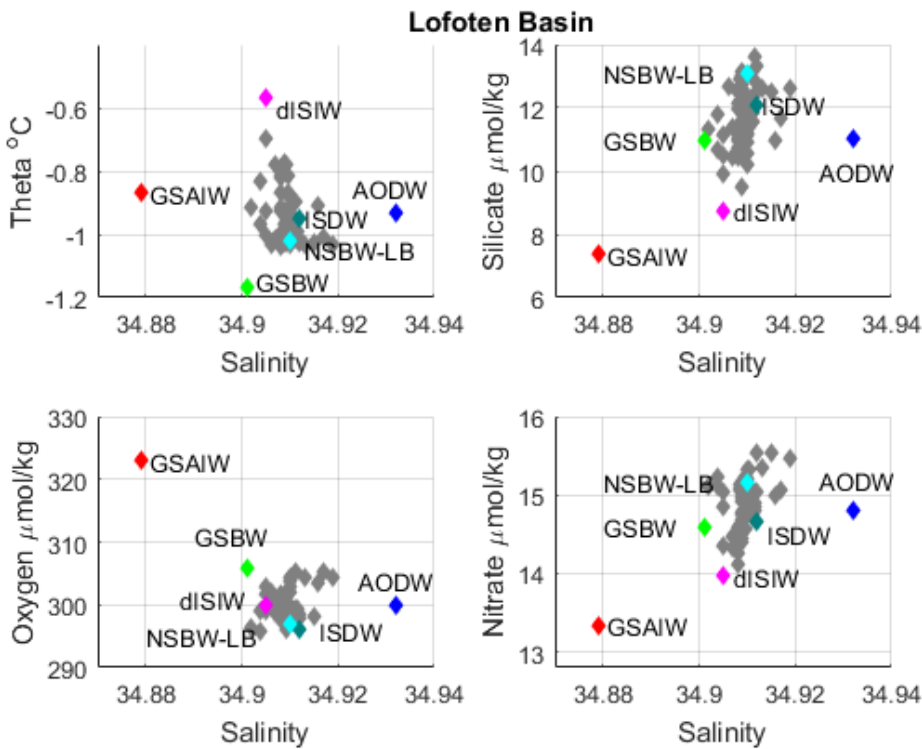


Figure 10: Potential temperature, oxygen and nutrients as functions of salinity for the Lofoten Basin, restricted for the time periode 90-99 and for depth>2000m. Grey dots represent deep water data, coloured dots represent source waters. NSBW-LB- Norwegian Sea Bottom Water-Lofoten Basin, GSAIW-Greenland Sea Arctic Intermediate Water, dISIW- dense Iceland Sea Intermediate Water, GSBW-Greenland Sea Bottom Water, ISDW- Iceland Sea Deep Water, AODW- Arctic Ocean Deep Water.

2.4 Uncertainties

Most of the uncertainties in the OMP analysis are connected with the definitions of source waters, and these are connected with environmental variability. Many of these variations are accounted for when calculating the weights. The parameter weights are dependent on how well the model can resolve the parameter through the variability of the source matrix. If such a parameter would differ greatly between different source water types, they will be given higher weights, as they will contribute more to the solution of the mixing equation. If now a water sample contains values that are outside the defined parameter ranges set by the source waters in a specific mixing situation, the method might assign water samples the wrong source water type. For example, if a water sample contains a value outside the parameter range for silicate, a high silicate source water will take its place. While this will make sense mathematically, it does not always make sense environmentally. A way of controlling this is through mass conservation residual of fit. A good fit is any analysis run that provides a mass conservation residual of fit $\leq 5\%$. This means that the included source waters can explain the analysed data, without other water masses significantly influencing the result (Tomczak & Poole, 1999). Anything above this value could indicate that the definition of the water masses is not good enough, or that the definitions are outdated. Almost all data in the analysis for all years and both basins end up below 5%, but there are some outliers. Analysis was first done for all years and depth larger than 2000 m, but individual OMP analysis was also done for 500 m layers between 1500-3500 m (Table 4).

It should be mentioned that some of the plots in Figure 9 look a bit unnatural, the same can be said for Figure 13, and this is a result of interpolation done in this thesis (due to fewer data points in the deeper layers). This problem is perhaps more evident for the nutrients, but all years were chosen to be included for its visual value.

Table 4: Mass conservation of fit per depth layer for the Norwegian Sea.

	1500-2000 m	2000-2500 m	2500-3000 m	3000-3500 m
Norwegian Basin	3%	3.5%	5%	6%
Norwegian Basin 2000s	4	2.4	7	9
Lofoten Basin	3%	3%	6%	10%
Lofoten Basin 2000s	4%	2.2%	3.5%	10%

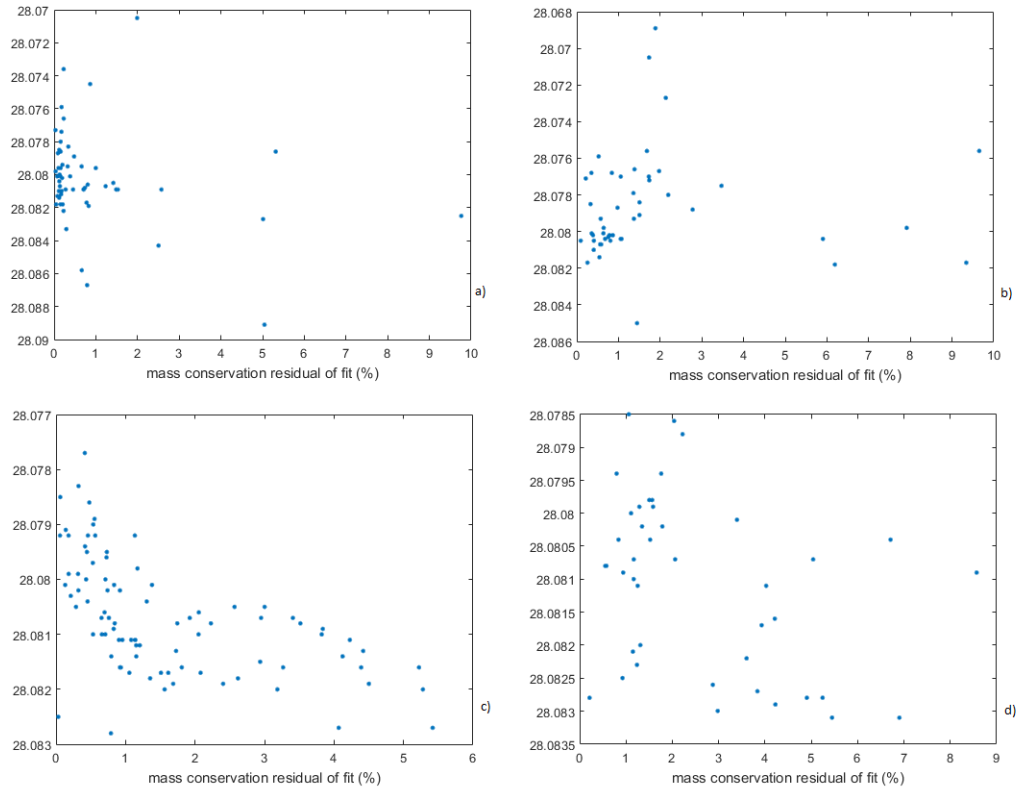


Figure 11: Mass conservation residual of fit against density (y axis) for a) Lofoten Basin (run for 1991-95,1999), a) Lofoten Basin (run for 2000, 2002, 2009), c) the Norwegian Basin (run for the years 1992-97), d) the Norwegian Basin (2002)

3. Results

3.1 Changes of the Norwegian Sea deep water

Norwegian basin:

Figure 12 shows a yearly averages of the six parameters used in the OMP analysis. Below 2000 m were we find the deep water (NSDW, NSBW-NB), the Norwegian Basin has changed during the course of the 1990s. From table 5 it is seen that salinity increased by 0.001 and temperature by 0.03 °C. Using Figure 12 a) and b) one can see that the changes are largest near the 2000 m layer. Oxygen averages did not differ and both time periods averaged 298 $\mu\text{mol/kg}$. Figure 12 c) shows a fluctuation of 10 $\mu\text{mol/kg}$ between the years 1992 and 1995. Table 5 shows that silicate decreased on average from the 1990s to 2002. From figure 12 d) we can see that this occurred in the upper part of the deep layer, and that there was an in fact and increase in silicate near basin floor (at about 3500 m). This is also seen for NSBW-NB (Table 2,3). Nitrate values increased from the 1990s to the 2000s, but

figure 12 e) shows a fluctuation in the 1990s, so that 1992,1993 and 2002 are of similar values. Phosphate stay close around 1 for all years in Figure 12 f) and does not change on average (table 5).

Lofoten basin:

Figure 13 shows a distribution for the six parameters used in the OMP analysis of the Lofoten Basin for the period 1991-95 and the years 2000, 2002, 2009. The average salinities did not change between the two decades, however there was an increase in temperature, similar to what was seen for the Norwegian Basin. This temperature increase was similar to the Norwegian Basin for the 1990s and early 2000s, but because of a large warming between 2002, and 2009 (Figure 13 b), the average warming is larger for the Lofoten Basin. Oxygen fluctuated around 300 $\mu\text{mol/kg}$ (Figure 13c), similar to observations of the Norwegian Basin, but was found to decrease on average between the two decades (Table 5). Silicate increased for the deeper layers on average (Table 5), but showed fluctuations (Figure 13d). For example, 1993 was had the lowest values, 1999 had the highest (between 13 and 14 $\mu\text{mol/kg}$) and 2009 made an “average” of the two. The last two nutrients, nitrate and phosphate also increased from the 1990s to the 2000s. It is easy to see from Figure 13 e) and f) that this increases steadily over the two periods.

Table 5: Mass conservation of fit per depth layer for the Norwegian Sea.

Source Waters	Salinity	Pot.-temp $^{\circ}\text{C}$	Density kg/m^3 .	Phosphate $\mu\text{mol/kg}$	Nitrate $\mu\text{mol/kg}$	Silicate $\mu\text{mol/kg}$	Oxygen $\mu\text{mol/kg}$
<i>1990-1999</i>							
NSDW-NB	34.909	-1.03	28.081	1.02	15.08	12.92	298
NSAIW-NB	34.896	-0.39	28.042	0.96	14.21	8.39	300
NSDW-LB	34.910	-1.01	28.081	1.00	14.88	12.23	300
NSAIW-LB	34.910	-0.92	28.077	0.99	14.71	11.45	300
<i>2000-2009</i>							
NSDW-NB	34.910	-1.00	28.081	1.02	15.31	12.88	298
NSAIW-NB	34.906	-0.80	28.069	1.00	14.81	10.53	299
NSDW-LB	34.910	-0.96	28.079	1.01	15.16	12.41	298
NSAIW-LB	34.907	-0.82	28.069	1.01	14.89	11.15	299

Abbreviations for water masses are: NSDW- Norwegian Sea Deep Water, NSAIW- Norwegian Sea Arctic Intermediate Water. Where NB and LB stands for Norwegian Basin and Lofoten Basin, respectively.

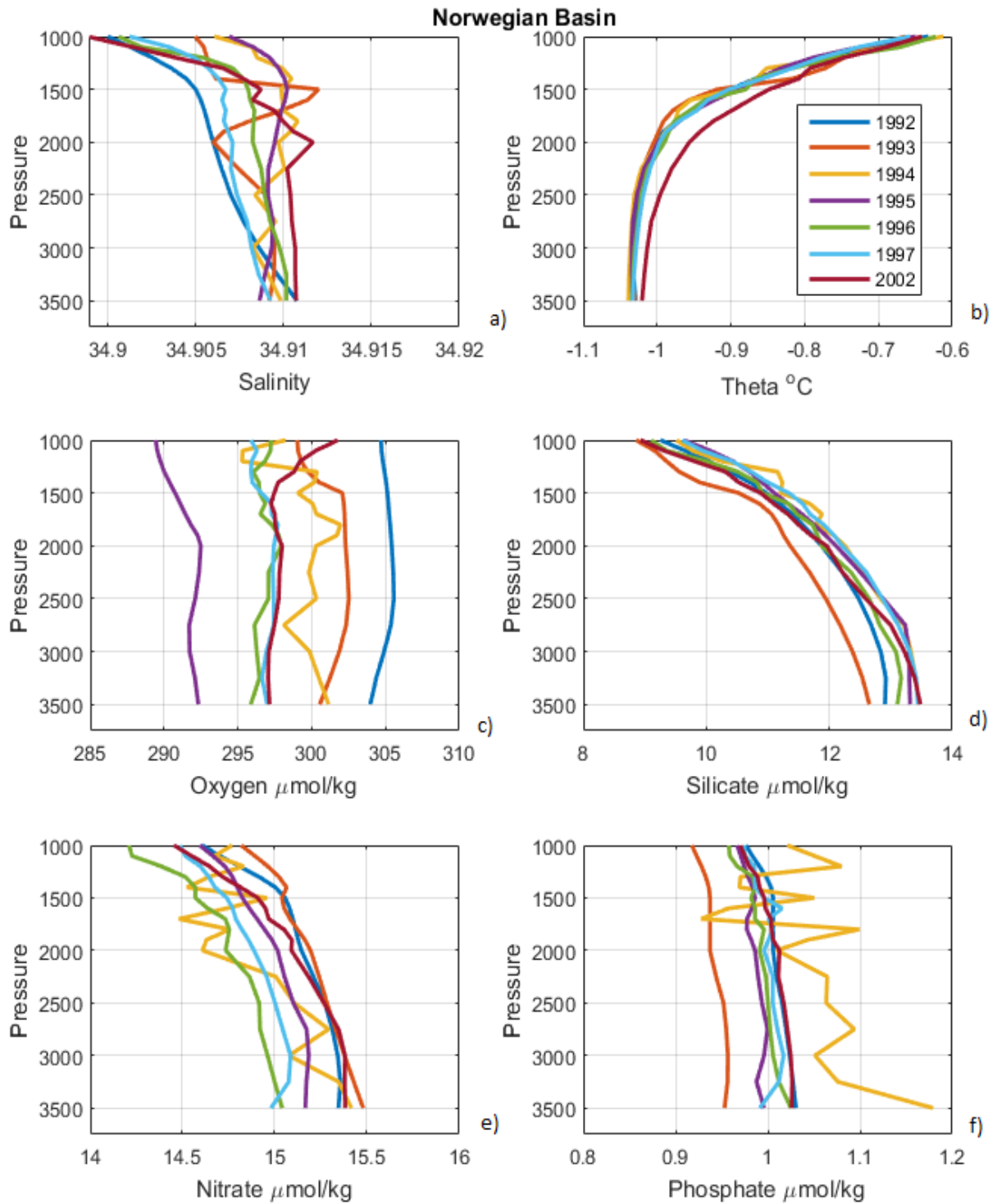


Figure 12: Yearly interpolated averaged values for the Norwegian Basin for the sample years 1992-97, 2002. a) Salinity, b) Potential temperature (theta), c) Oxygen, d) Silicate, e) Nitrate, f) Phosphate.

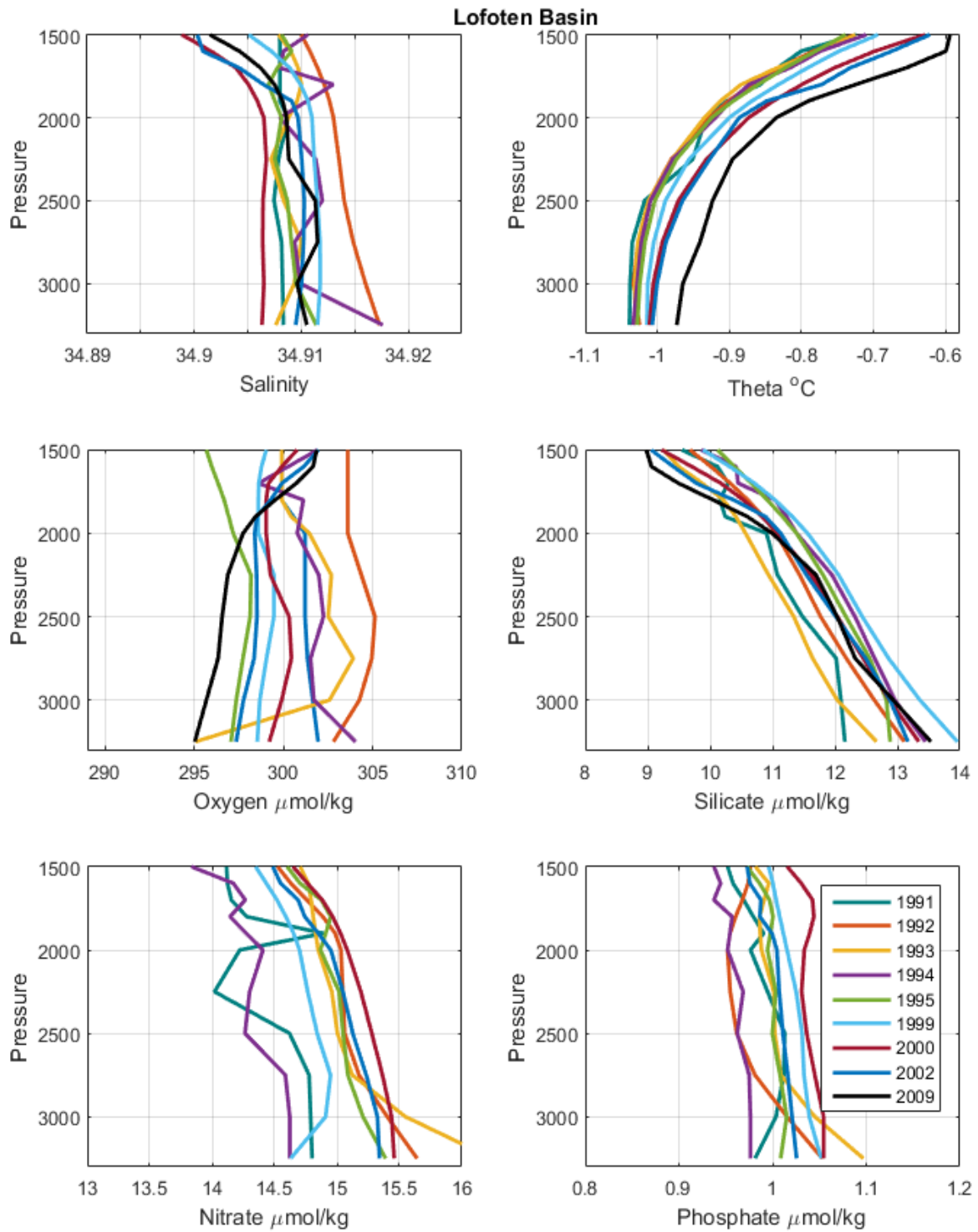


Figure 13: Yearly interpolated averaged values for the Lofoten Basin for the sample years 1991-95,2002, 2002,2009. a) Salinity, b) Potential temperature (theta), c) Oxygen, d) Silicate, e) Nitrate, f) Phosphate.

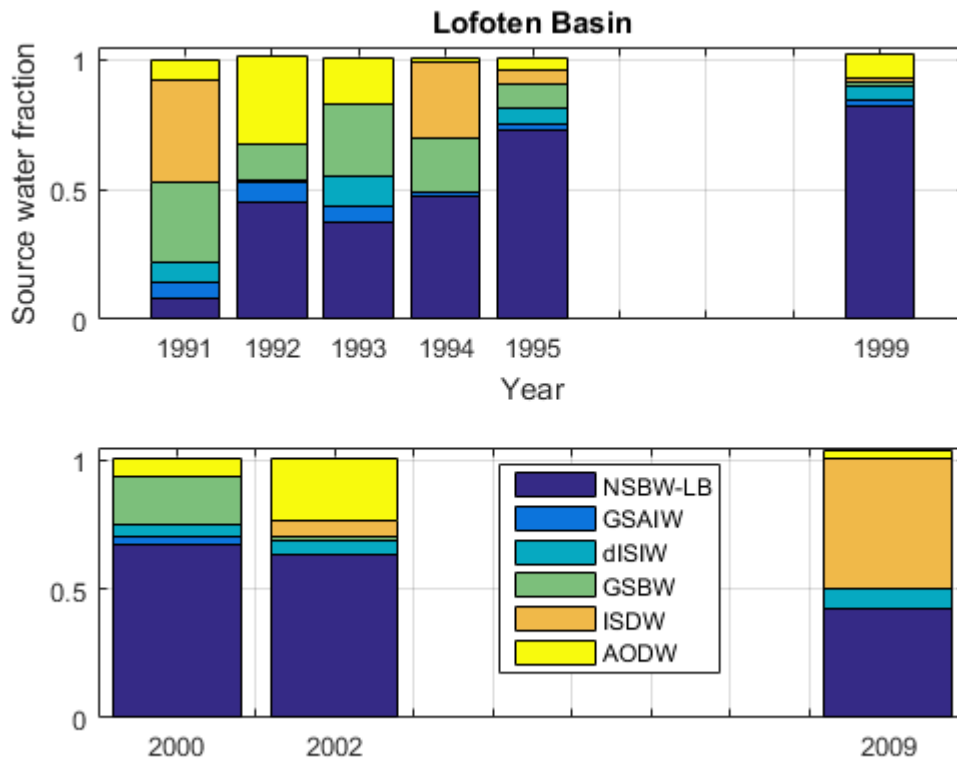


Figure 14: Source water fraction in the Lofoten Basin for the period 1991-2009. Abbreviations of water masses are: AODW- Arctic Ocean Deep Water, AOIW- Arctic Ocean Intermediate Water, dISIW- dense Iceland Sea Intermediate Water, GSAIW- Greenland Sea Arctic Intermediate Water, GSBW- Greenland Sea Bottom Water, GSDW- Greenland Sea Deep Water, ISDW- Iceland Sea Deep Water, NSBW-LB- Norwegian Sea Bottom Water-Lofoten Basin.

3.2 Source waters of the Norwegian Sea

When viewing the fraction of source waters over the two decades a pattern evolves for the Lofoten Basin. In Figure 14, the increasing fraction of NSBW-LB is clearly visible. In 1991 ISDW and GSBW make up most of the deep water fraction. During 1992-1995 NSBW-LB dominates with close to 50% of the source water fraction, with AODW, GSBW, and ISDW being the second largest in consecutively. NSBW-LB increases to almost 90%, near the end of the decade. For the 2000s NSBW-LB a clear decrease, and in 2009 the dominating source water is ISDW.

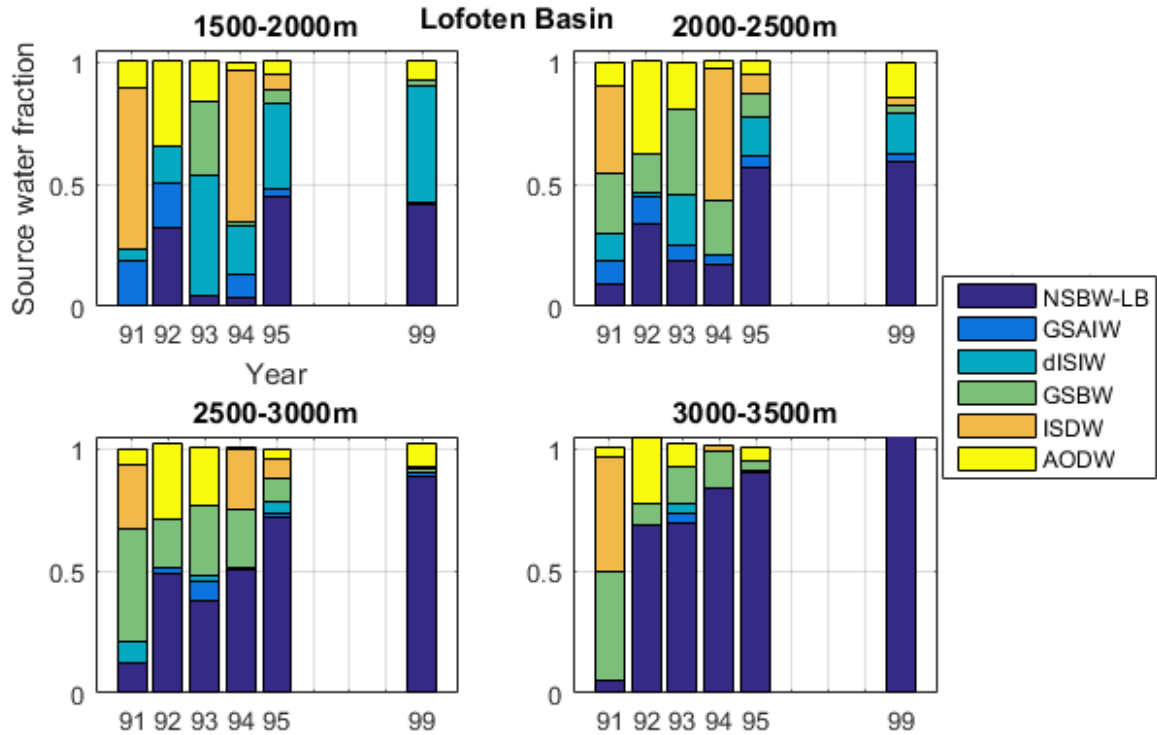


Figure 15: Source water fraction in the Lofoten Basin for the period 1991-1999. Each frame shows distribution over different depths, from 1500m and towards the bottom. Abbreviations of water masses are: AODW- Arctic Ocean Deep Water, AOIW- Arctic Ocean Intermediate Water, dISIW- dense Iceland Sea Intermediate Water, GSAIW- Greenland Sea Arctic Intermediate Water, GSBW- Greenland Sea Bottom Water, GSDW- Greenland Sea Deep Water, ISDW- Iceland Sea Deep Water, NSBW-LB- Norwegian Sea Bottom Water-Lofoten Basin.

Figure 15 shows the results at four depth intervals from 1500 m. In 1991 and 1994- the upper deep layers between 1500m-2500 m, contain fractions of ISDW that are over 50%. In 1993, 1995 and 1999 the most dominant source water was dISIW, with close to a 50 % source water fraction. Between 2000-2500 m NSBW-LB starts to get increasingly important, and dominates for the years 1995, 1999. In the second deepest layer, there was almost no contribution from the intermediate water masses, and besides the increasing fraction of NSBW-LB, GSBW and AODW were the dominating source waters. In the deepest layer NSBW-LB completely dominates as a water source during except in 1991, where the deep water is made up of an almost 50-50 mix of ISDW and AODW. One interesting thing here is how little NSBW-LB there is in 1991 compared to the remaining years. The opposite is true for 1999 where the entire layer is NSBW-LB.

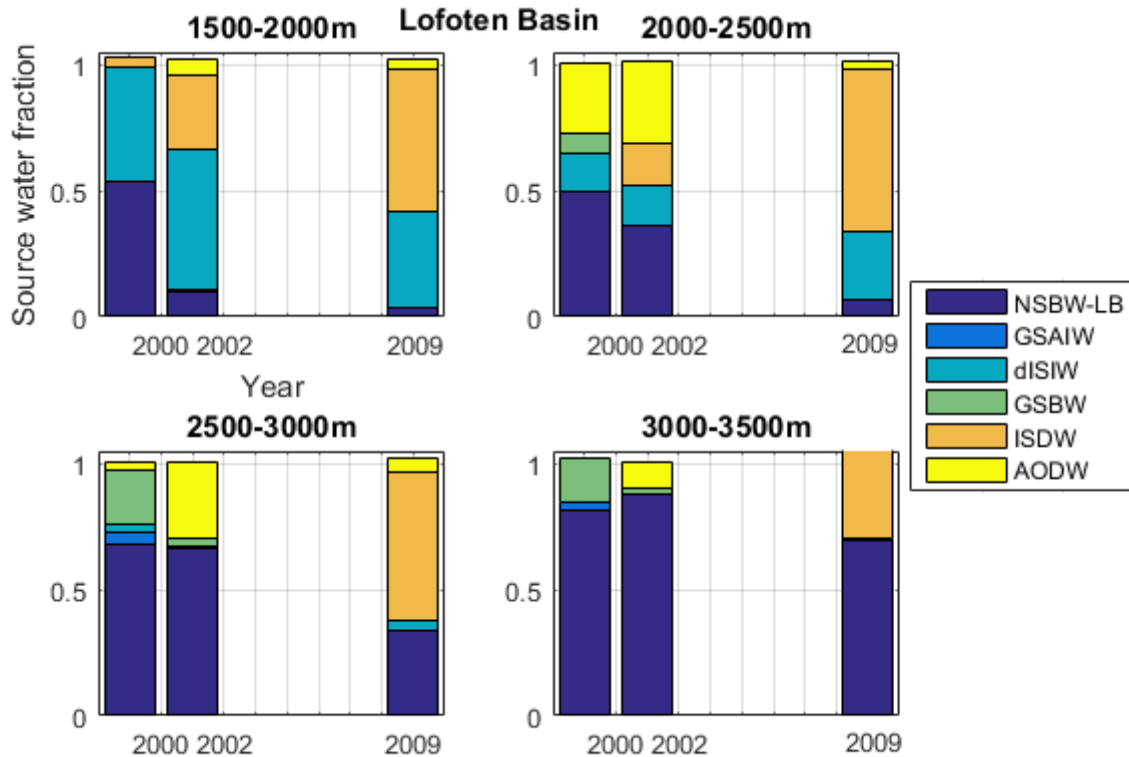


Figure 16: Source water fraction in the Lofoten Basin for the period 2000-2009. Each frame shows distribution over different depths, from 1500m and towards the bottom. Abbreviations of water masses are: AODW- Arctic Ocean Deep Water, AOIW- Arctic Ocean Intermediate Water, dISIW- dense Iceland Sea Intermediate Water, GSAIW- Greenland Sea Arctic Intermediate Water, GSBW- Greenland Sea Bottom Water, GSDW- Greenland Sea Deep Water, ISDW- Iceland Sea Deep Water, NSBW-LB- Norwegian Sea Bottom Water- Lofoten Basin.

The layered source water fraction for the Lofoten Basin for the years 2000, 2002 and 2009 are presented in Figure 16. During the 2000s the upper deep layers between 1500m-2000 m, contained close to 50% source water fraction for 2000 and 2009, and more than 60% in 2002. The fraction of NSBW-LB decreases towards the end of the decade, and was close to 0 in 2009, where ISDW dominated.

Unlike the 1990s it does seem like the amount decreases here rather than increase. In the depth layer 2500-3000 m the decrease in NSBW-LB fraction amount is clearer, compared to what was the case for the 1990s at the same depth. In 2009 the NSBW-LB is not as heavily pronounced in the deepest layers as it was in 1999 and only consists of about 60% of the source water from 3000 m and to the ocean floor.

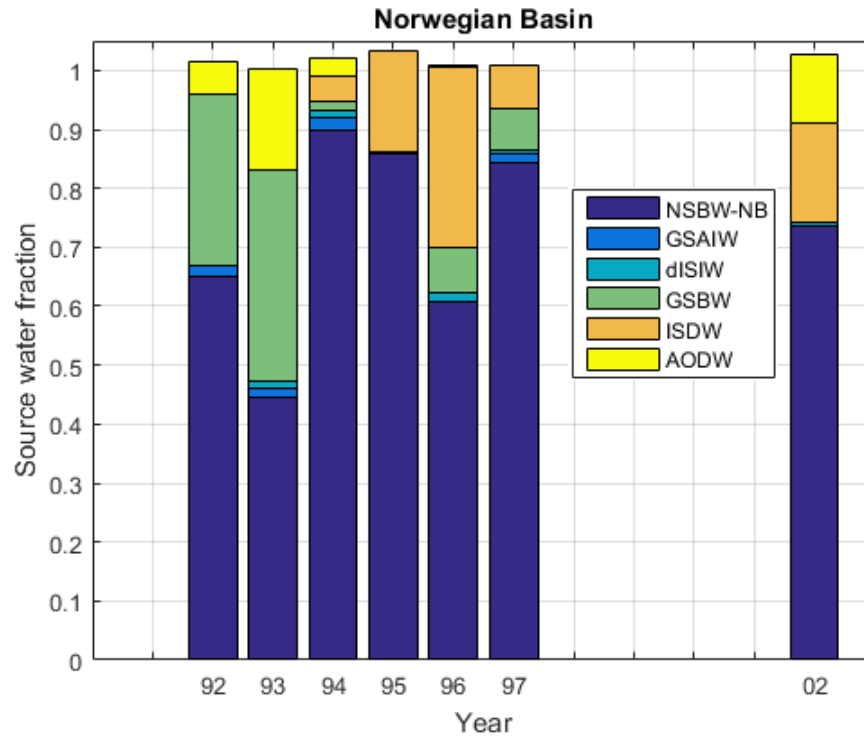


Figure 17: Source water fraction in the Norwegian Basin for the period 1991-2002. Abbreviations of water masses are: AODW- Arctic Ocean Deep Water, AOIW- Arctic Ocean Intermediate Water, dISIW- dense Iceland Sea Intermediate Water, GSAIW-Greenland Sea Arctic Intermediate Water, GSBW-Greenland Sea Bottom Water, GSDW-Greenland Sea Deep Water, ISDW- Iceland Sea Deep Water, NSBW-LB- Norwegian Sea Bottom Water-Lofoten Basin.

The fraction values for the Norwegian Basin are seen in Figure 17. Unlike what was seen for the Lofoten Basin, there does not seem to be an increasing trend in the fraction of NSBW-NB during the 1990s. Instead the values fluctuate between 50% and 90% of the total source water fraction. In 1992 and 1993 the other dominant source water for the Norwegian Basin was the GSBW. For 1995 and 1996 as NSBW-NB decrease, there is an increase in the amount of ISDW. For the last recorded year, 2002, there is a clear dominance of NSBW-NB, but it has decreased from 1997. It makes up more than 70% of the total source water fraction in the Norwegian Basin. This is similar to the fraction value in Lofoten Basin for 1999, but with larger fraction of ISDW.

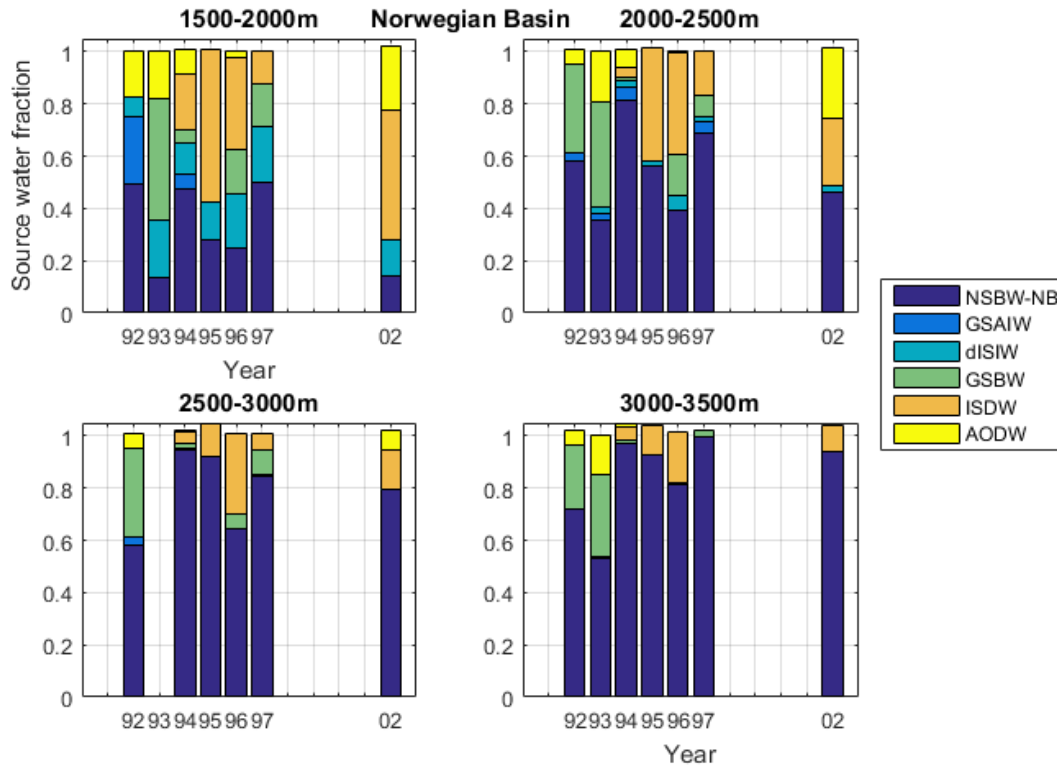


Figure 18: Source water fraction in the Norwegian Basin for the period 1992-1997, 2002. Each frame shows distribution over different depths, from right above deep water level and towards the bottom. Abbreviations of water masses are: AODW- Arctic Ocean Deep Water, AOIW- Arctic Ocean Intermediate Water, dISIW- dense Iceland Sea Intermediate Water, GSAIW- Greenland Sea Arctic Intermediate Water, GSBW- Greenland Sea Bottom Water, GSDW- Greenland Sea Deep Water, ISDW- Iceland Sea Deep Water, NSBW-LB- Norwegian Sea Bottom Water-Lofoten Basin.

In Figure 18 the layered fractions of source water are displayed. For the upper layer between 1500-2000 m NSBW-NB consists of between 20-50% of the total source water in the Norwegian Basin. Here we have a larger fraction of ISDW in the years 1995, 1996 and 2002, while GSBW dominates in 1993. Intermediate waters had fractions of up to 25%, indicating mixing with the deeper layers. Below this, in the 2000-2500 m layer, the dominance of NSBW-NB becomes clear, and it was the largest source water most years. In 1993 however it is GSBW that dominates, and ISDWs fraction is as larger or slightly larger in 1995. In the two deepest layers NSBW-NB had fractions of close to 70 % for all years. 1992 and 1993 showed fraction of GSBW close to 20 % (for the 2500-3000m layer data are missing from 1993), and ISDW had fractions around 10% for the remaining period.

4. Discussion

4.1 Changes of the Norwegian Sea deep water

The Norwegian Basin was sampled during the period 1992-1997, and the year 2002. The basin experienced a slight increase in salinity from 1992 to 2002 (figure 12). For potential temperature there was an increase from 1992 to 2002, something that was also seen in the Lofoten Basin (Figure 13). For both basins it was the most recent years that were the warmest (1996, 1997

and 2002 for NB, 2000,2002 and 2009 for LB). It appeared as if the warming in the Lofoten Basin was larger than what was true for the Norwegian Basin, but this was most likely due to the 2009 data. Because of the close relationship between these two basins (Swift & Koltermann, 1988; Blindheim & Rey, 2004), it is not unlikely that a similarly increased warming could have been seen for the Norwegian Basin if it was sampled at same time. Increase in deep water temperature has been seen in other parts of the Nordic Seas (Blindheim & Rey, 2004; Karstensen et al., 2005; Ronski & Budèus, 2005). Blindheim & Rey (2004) suggested for the Greenland Sea, that a lack of deep convection allowed for an increase of AODW in the GSDW and GSBW, making it saltier, higher in silicate and lower in oxygen. They further suggested that the increase in temperature could influence the NSDW, but to a smaller degree due to mixing along the way. Østerhus & Gammelsrød (1999) observed an increase in potential temperature of 0.1 °C for the NSDW between 1200-2000 m at Ocean Weather Station M (66N, 2E), from the mid-1980s to 1998. At the same station they noticed a lower increase of about 0.02 °C for the greater depths, from around 3000 m. It is possible that a change of temperature in the Greenland Sea could be the cause of the increase seen in the Norwegian and Lofoten Basins. The change in salinity did not seem to occur in the Norwegian Sea, to the same magnitude as it does in the Greenland Sea. This is to be expected as GSDW and GSBW have been much fresher, causing any change in salinity from incoming AODW to be large. Although the Norwegian Basin increased in salinity, it did not change in the Lofoten Basin. Oxygen in the Norwegian Basin fluctuates below 1000 m, however there is a decrease in oxygen from 1992- 2002, of almost a 10 µmol/kg. A similar profile can be seen for the Lofoten Basin, only here the 2009 value, is the lowest. This could indicate that the oxygen content of the Norwegian Basin might be lower than reported. Silicate steadily increases from 2000 m to the bottom in both of the basins. The Norwegian basin has a higher total amount of silicate, due to a sharper gradient, but near the bottom both basins have similar values around 13. Both basins show an increase of more than 1 µmol/kg, from 1992-2002 for the Norwegian Basin and from 1991-2009 in the Lofoten Basin. The increase in silicate were observed by Blindheim & Rey (2004). These values are among if not the highest in the entire Nordic Seas. Some local process must be the cause of this, as no known source waters show any matching values. These large values of silicate are mentioned in Blindheim & Rey (2004), with the possible explanation (given for the Norwegian Basin for 1994) being that it comes from modified CBDW, entering at depths between 1400 m and 2000 m. The layer of entry is based on matching salinity maximums of 34.910 found near the Iceland Plateau and in the Norwegian Basin CBDW entering the Iceland Sea via the EGC (Aagaard et al., 1991, Buch et al.,1996 undergoes transformation, but the processes increasing the silicate levels, are not well understood. High retention time in the Iceland Seas was given as a likely reason for the high levels of nutrients and low oxygen. If this is indeed the source of the high silicate values found in the Norwegian Sea, there must still be a process that increases these values further. Nitrate and phosphate also increased in the Norwegian Sea. This could be connected with the increase of nutrients seen for the possible source areas, e.g Greenland Sea, Iceland Sea (Table 2,3). The unknown process creating higher silicate in the Iceland and Norwegian Sea, could possibly be a result of remineralization of nutrients, but this is simply speculation.

4.2 Source waters of the Norwegian Sea

Blindheim & Rey (2004) suggested that because of the different composition of the deep water in the Norwegian Basin compared to the Lofoten Basin, that the Lofoten Basin was more influenced by the GSBW during the 1990s. This claim was based on the Norwegian Basin having slightly higher salinity, lower oxygen and higher silicate. Although this salinity difference was not seen (table 5), the suggestion might be true for some years. The GSBW is seen up until 1995 in the Lofoten Basin, and appeared again in 2000. The Norwegian Basin however, had a higher fraction of GSBW than the Lofoten Basin in 1993. After this GSBW only appeared in small fractions. The intermediate source waters contribute more in the Lofoten Basin than in the Norwegian, but are in general not important beyond the 2000m layer (figure 15, 16, 18), with the exception of some years

for Lofoten. The biggest contributing intermediate water was the dISIW. AODW had large fractions (figure 15, 16) in the Lofoten Basin during 1992, 1993 and 2002, but is generally the least important of the three deep waters in the Norwegian Sea. ISDW is the most important source water, next to NSBW-LB/NB, especially in 1991 and 2009, for the Lofoten Basin, where it made up close to 50% of the source water fraction. In the Norwegian Basin it takes over as the second largest fraction from 1995, and has a fraction around 20%. The relative importance of ISDW in the Norwegian Basin during the mid to late 1990s, could indicate that the suggestion made by Blindheim & Rey (2004) could be correct. The depth of entry suggested by Blindheim & Rey (2004), somewhat matches with where most ISDW is found for the Norwegian Basin at the same time. In any case it can lead to one answer as to why nutrient content is so high in the Norwegian Sea. The NSBW-LB/NB becomes the dominating water source in the deep, beyond 2500m. From this depth it dominated for all years except one year in the Lofoten Basin 1991. The contributions from the other three deep waters mostly occurs between 2000-3000m. During the 1990s the content of NSBW-LB increased until most of the deep water was considered NSBW-LB, then increasing fractions of AODW and GSBW caused a decrease at the start of the 2000s. This increase and decrease of NSBW can in some ways be seen in the Norwegian Basin but the pattern is not as clear. Turrell et al. (1990) found that a decreasing amount of deep water from the Greenland Sea had important negative outcome for ISOW. As less GSBW supplied the NSDW, the depth of NSDW increased to a deep that made it difficult to supply the Faroe Shetland Channel Bottom Water. This water is in part made up of NSDW, making up 60% of it during 1970-1985, but that this had changed to about 40 %. The decreasing amount of GSBW in both basins and relative absence of GSBW after 2002, could further impact the amount NSDW that passes through the Faroe-Shetland Channel.

5. Summary and conclusions

The Norwegian Sea Deep Water is an important contributor to the ISOW and an accurate description of changes in its build up as well as a knowledge of its sources is important. A warming of the NSDW has been observed in both of the Norwegian Basins for the two most recent decades on record, as well as a decrease in oxygen and increase of nutrients. The warming is likely due to warmed source waters entering, possibly from the Greenland Sea.

Results of the OMP analysis of the NSDW shows that the classical definition of its composition is not accurate enough. This is mainly due to the fact that the nutrient compositions of EBDW and GSDW cannot explain the high amount of nutrients seen in the Norwegian Sea. The suggestion from Blindheim & Rey (2004) of CBDW being transformed in the Iceland Sea to a point where it gains values more similar to the NSDW-NB does give an answer to some of the higher nutrient values. But this explanation was only given for the Norwegian Basin. Mixing between basins does occur to some extent, but in order to explain the high silicate values of the Lofoten Basin a similar contribution from the Iceland Sea must happen here as well. Results presented shows that ISDW is an important source to the NSBW in both of the Norwegian Basins, but further transformation must occur in the Norwegian Sea. This is clear as the NSBW-LB/NB still makes up most of the deep water in the Norwegian Sea for both decades. The yearly distribution of the source water fraction of the deep water also shows that sources contribute in different volumes. The GSBW seems to be more important as a source for the early 1990s while ISDW is more important for the later years, showing variation in the deep water build up. Based on results and previous work, a mixture of these source waters along with NSBW seems most likely sources to the NSDW. In order to get an accurate source water description, the understanding of the high nutrient values in the Norwegian Sea deep is vital. A more detailed view of this, be it by remineralization or other

possibilities, must somehow be accounted for if additional OMP analysis are to be attempted for this region. Use of CFCs might add information regarding if NSBW is old NSDW and should be investigated. The decreasing amount of NSDW in the ISOW (Turrell et al., 1999) documented in the past, could be have changed. The relative absence of GSBW for the NSBW-LB/NB have a further impact on the amount of deep water passing into the Faroe-Shetland Channel, and should be investigated. Regular sampling of the Norwegian Sea Deep Water, in the Norwegian basins should be provided as the amount of regular data is vital to the understanding of its build up.

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