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Characteristics of Water Masses in the Atlantic Ocean based on GLODAPv2 data

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Abstract: The **c**haracteristics of the main water masses in the Atlantic Ocean are investigated and defined as Source Water Types (SWTs) from their formation area by six key properties based on the GLODAPv2 observational data. These include both conservative (potential temperature and salinity) and non-conservative (oxygen, silicate, phosphate and nitrate) variables. For this we divided the Atlantic Ocean into four vertical layers by distinct potential densities in the shallow and intermediate water column, and additionally by concentration of silicate in the deep waters. The SWTs in the upper/central water layer originates from subduction during winter and are defined as central waters, formed in four distinct areas; East North Atlantic Central water (ENACW), West North Atlantic Central Water (WNACW), East South Atlantic Central Water (ESACW) and West South Atlantic Central Water (WSACW). Below the upper/central layer the intermediate layer consist of three main SWTs; Antarctic Intermediate Water (AAIW), Subarctic Intermediate Water (SAIW) and Mediterranean Overflow Water (MOW). The North Atlantic Deep Water (NADW) is the dominating SWT in the deep and overflow layer, and is divided into upper and lower NADW based on the different origins and properties. The origin of both the upper and lower NADW is the Labrador Sea Water (LSW), the Iceland-Scotland Overflow Water (ISOW) and Denmark Strait Overflow Water (DSOW). Antarctic Bottom Water (AABW) is the only natural SWT in the bottom layer and this SWT is redefined as North East Atlantic Bottom Water (NEABW) in the north of equator due to the change of key properties, especial silicate. Similar with NADW, two additional SWTS, Circumpolar Deep Water (CDW) and Weddell Sea Bottom Water (WSBW), are defined in the Weddell Sea in order to understand the origin of AABW. The definition of water masses in biogeochemical space is useful for, in particular, chemical and biological oceanography to understand the origin and mixing history of water samples.

Key Words: Water Mass, Source Water Types, GLODAP, Atlantic Ocean

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1. Introduction

Properties of water in the ocean are, obviously, not uniformly distributed so that different regions and depths (or densities) are characterized by different properties. Bodies of water with similar properties often share a common formation history and are referred to as water masses, or, more generally, sea water types. Understanding of the distribution and variation of water masses play an important role in several disciplines of oceanography, for instance while investigating the thermohaline circulation of the world ocean or predicting climate changes (e.g. Haine and Hall, 2002; Tomczak, 1999). Particularly important is the concept of water masses for biogeochemical and biological applications where the transformation of properties over time can be successfully viewed in the water mass frame-work. For instance, the formation of Denmark Strait Overflow water in the Denmark Strait could be described using mixing of a large number of water masses from the Arctic Ocean and the Nordic Seas (Tanhua et al., 2005). In a more recent work, Garcia-Ibanez et al. (2015) considered 14 water masses combined with velocity fields to estimate transport of water mass, and thus chemical constituents, in the north Atlantic. Similarly, Jullion et al. (2017) used water mass analysis in the Mediterranean Sea to better understand the dynamics of dissolved Barium. Also, Wüst and Defant (1936) illustrated the stratification and circulation of water masses in the Atlantic Ocean based on the observational data from Meteor Cruise 1925-1927. Based on research during last few decades, Tomczak (1999) summarized the history of the water mass research and provided an outlook for the evolution of water mass research. In this paper we use the concepts and definitions of water masses as given by Tomczak (1999).

The definition of a water mass is a body of water that originates in a particular area of the ocean with a common formation history. Water masses share common properties such as temperature, salinity and biogeochemical variables that are distinct from surrounding bodies of water (e.g. Helland-Hansen, 1916; Montgomery, 1958) and have a measurable extent both in the vertical and horizontal, and thus a quantifiable volume. Since water masses are surrounded by other water masses there will be mixing (both along and across density surfaces) between the water masses, so that away from the formation regions one tend to find mixtures of water masses with different properties compared to the ones in the formation area. Early work by Schaffer and JACOBSEN (1927) and Defant (1929) illustrated the application of T-S relationship in the oceanography. This concept has been redefined over time and in Emery and Meincke (1986), for instance, the water masses were divided into upper, intermediate and deep/abyssal layers including the depth to the T-S relationship. With the development of observational capacities for a range of variables, definition of water masses is not only limited by the T-S-P relationship. New physical and chemical parameters, both conservation and non-conservative, are added in the water mass concept e.g. (Tomczak, 1981; Tomczak and Large, 1989). These additional variables exhibit different importance in defining a water masses but are complementary to each other and provide a more solid basis for the water mass definition.

The ocean is thus composed a large number of water masses, these are however not simply piled up in the ocean like bricks. In fact, there are no clear boundaries between them. Or, in other words, there is a gradual and mixed process between water masses (Castro et al., 1998). As a direct result another concept was introduced: Source Water Types (SWTs). SWTs describe the original properties of water masses in their formation area, and can thus be considered as the original form of water masses (Tomczak, 1999).

It is important to realize that while water masses have a defined volume and extent, a water type is only a mathematical definition that does not have a physical extent. A SWT is defined based on a number of properties

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and their variance, or standard deviation (Tomczak, 1999). Knowledge of the properties of the SWTs is essential in labeling water masses, tracking their spreading and mixing progresses. Accurate definition and characterization of SWTs is an essential step for performing any water mass mixing analysis, such as the Optimum Multi-parameter (OMP) analysis (Tomczak and Large, 1989). In practice though, defining properties of source water types and water masses is often a difficult and time-consuming part of water mass analysis, particularly when analyzing data from a region distant from the water mass formation regions. In order to facilitate water mass analysis we use the Atlantic data from the data product GLODAPv2 (Lauvset et al., 2016) to identify and define source water types for the most prominent water masses in the Atlantic Ocean based on 6 commonly measured physical and biogeochemical variables. The aim of this work is to facilitate water mass analysis and in particularly we aim at supporting biogeochemical and biological oceanographic work in a broad sense. We realize that we define the SWTs in a static sense, i.e. we assume that they do not change with time, and that our analysis is relatively course in that we do not consider subtle differences between closely related SWTs but rather paint the picture with a rather broad brush. Studies looking at temporal variability of water masses, or water mass formation processes in detail, for instance, may find this study useful but will certainly want to use a more granular approach to water mass analysis in their particular area.

In a companion paper (Liu and Tanhua, 2018) we will use the here defined Atlantic Ocean SWTs to estimate the distribution of the water masses in the Atlantic Ocean based on the GLODAPv2 data.

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2. Data and Methods

In this study we use six key variables to define source water types (SWTs) in Atlantic Ocean, including two conservative variables, potential temperature (θ) and salinity (S), and four non-conservative variables, silicate, oxygen, phosphate and nitrate. We utilize the GLODAPv2 data product (Lauvset et al., 2016) to quantify the properties and related standard deviation of these variables for Atlantic Ocean SWTs. The GLODAPv2 data product is a compilation of interior ocean carbon relevant data from ship-based observations and includes data on oxygen and nutrients. The data in the GLODAPv2 product has passed both a primary quality control (aiming at precision of the data) and a secondary data quality control (aiming at the accuracy of the data). The data product that we use in this work thus uses adjusted values to correct for any biases in data. The methodologies for the QC processes in GLODAPv2 are similar to those used for the CARINA data product and are described in detail in (Key et al., 2010). Through these QC routines, the GLODAPv2 product is unique in its internal consistency, and is thus an ideal product to use for this work aiming at definitions of major water masses and source water types in the Atlantic Ocean. Armed with the internally consistent data in GLODAPv2, we utilize previously published studies on water masses and their formation areas to define areas and depth / density ranges that can be considered to be representative samples of a SWT. As a second step we characterize the SWT in a 6 parameter space by quantifying the concentrations of these variables and use the standard deviation as a measure of the variability of each SWT and variable combination.

3 Source Water Types (SWTs) in the Atlantic Ocean

In line with the results from Emery and Meincke (1986) and from our interpretation of the observational data from GLODAPv2, we consider that the water masses in the Atlantic Ocean are distributed in four main vertical layers (Figure 1) roughly separated by surfaces of equal density. Potential density is the main basis to divide the shallow layers whereas for the deep and bottom layers the concentration of silicate is additionally used to distinguish these layers. In this concept we do not consider the mixed layer as its properties tend to be strongly variable on seasonal time-scales so that other methods to characterize the water masses is needed, mostly based on geographic region. The Upper Layer is the shallowest layer (i.e. lowest density) under consideration and is located within upper 500-1000m of the water column but below the mixed layer. The Intermediate Layer is located between ~1000 to 1500/2000m, below the Upper Layer. The Deep and Overflow layer occupies the layer roughly between 2000-4000m of the Atlantic Ocean. The Bottom Layer is the deepest layer, mostly located below 4000m, and is often characterized by high silicate concentrations. In this section we will identify key SWTs in each of the four layers. Table 1 lists the four layers and the water masses that we consider in this study. The table also lists the selection criteria that we used to define a Source Water Type in pressure, potential temperature or density space, for some SWTs, key properties such as salinity, oxygen or silicate are also necessary, in order to characterize the biogeochemical properties as well.

During our narrative of each SWT we will display four figures that will guide us to a more intuitive understanding of the SWTs: (a) maps of all GLODAPv2 station locations marked as light gray dots where stations within the area of formation that we consider are marked in red and stations with any samples within the desired properties as defined by Table 1 in blue, (b) the T-S relationship with the same color coding, (c) depth profiles of the 6 variables under consideration (same color coding), and (d) bar plots of the distribution of the samples within the criteria for a SWT. In the bar plot we have added a Gaussian curve to the distribution derived from the average and standard deviation of the distribution (the amplitude of the curve defined as 2/3 of the highest bar). The plots of properties vs pressure provides an intuitive understanding of each STW compared to others in the same region. The properties distribution and the Gaussian curve will help us to visually determine and confirm the SWT property values and associated standard deviation.

3.1 The Upper Layer, Central Waters

The Upper Layer is occupied by four SWTs called central waters that are known to be formed by subducted into the thermocline (Sprintall and Tomczak, 1993; Tomczak and Godfrey, 2013) into the interior of the ocean (Pollard et al., 1996). Figure 2 illustrate a schematic of the main currents in this layer and the main formation regions of the central waters in the Atlantic Ocean. Water masses or SWTs in this layer can be easily recognized by their linear T-S relationship (Pollard et al., 1996; Stramma and England, 1999). In this study, we define upper layer water masses to be located above potential density isoline of 27.0 kg/m^3 (see Fig 3.0), but below the mixed layer. The formation and transport of the Central Water is influenced by the currents in the shallow layer and finally forms a relative distinct body of water in both the horizontal and vertical. Mode Waters, on the other hand, are considered as the precursor or the prototype of the central waters (Alvarez et al., 2014; Cianca et al., 2009). In this study we will refer to Mode Waters in the description in defining or formation of the central waters but do not relate to their details.

3.1.1 Eastern North Atlantic Central Water (ENACW)

The main water mass in the upper layer of the region east of the Mid Atlantic Ridge (MAR) is the East North Atlantic Central Water (ENACW) (Harvey, 1982). This water mass is formed during winter and gets subducted in the seas west of Iberian Penisular. In addition, one component of the Subpolar Mode Water (SPMW) is carried by the south branch of North Atlantic Current (Figure 3a) and mixed in ESAW contributing to the properties of this water mass (McCartney and Talley, 1982) so that ENACW shows a typical linear T-S relationship (Pollard et al., 1996). ENACW advects in the general southern direction along the south branch of the North Atlantic Current (Arhan, 1990), passes northwest Africa, and then turns southwest into Canary basin. In the vertical scale, ENACW occupies at the upper ~500m with a relative low salinity, while SAIW is often occupying the water column below ENACW, often with contribution of MOW from the east in the intermediate depth (Garcia-Ibanez et al., 2015; Pollard et al., 1996; Pollard and Pu, 1985; Prieto et al., 2015). This straticication can also be clearly seen in the salinity/depth plot of Figure 3c where the MOW is primarily characterized by high salinity (see also Figure 9c and discription of MOW).

In our analysis, we follow the analysis of Pollard et al. (1996) and choose latitude between 39 and 48 °N and between 15 and 25 °E of longitude (east of Mid-Atlantic-Ridge) as the formation area of ENACW (Figure 3a). Based on the work of (Pollard and Pu, 1985) we choose potential density, σ_θ = 26.50 kg/m^3 as higher boundary and σ_θ = 27.30 kg/m^3 as the lower boundary to define ENACW in our analysis.

In Figure 3b, we can see clearly the linear T-S distribution of this water masses, consistent with Pollard et al. (1996) and the definition of ENACW$_{12}$ in Garcia-Ibanez et al. (2015). In Garcia-Ibanez et al. (2015), there is another definition ENACW$_{16}$, but water samples show a discrete distribution warmer than 16 °C by GLODAPv2 data set in this region, so also samples with potential temperature below 16 °C are selected in this study. As

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shown in Figure 3c, ENACW dominates the upper 500m depth. The main character of ENACW is the large potential temperature and salinity ranges and low nutrients (especially low in silicate).

3.1.2 Western North Atlantic Central Water (WNACW)

Western North Atlantic Central Water (WNACW) is another SWT formed during winter through subduction (McCartney and Talley, 1982; Worthington, 1959). WNACW is formed at the south flank of the Gulf Stream (Klein and Hogg, 1996) and is in some literatures referred to as 18 ° water since a potential temperature of around 18 °C and salinity around 36.5 are standard features of this SWT (Talley and Raymer, 1982). In general, ocean water in the Northeast Atlantic has higher salinity than in the Northwest Atlantic due to the stronger winter convection (Pollard and Pu, 1985) and input of MOW (Pollard et al., 1996; Prieto et al., 2015). However, for the central waters, we find the opposite. WNACW has a significantly higher salinity than ENACW by 0.9 PSU units. This is due to a number of reasons, such as different latitudes of formation; WNACW is formed in lower latitude than ENACW so that surface water with higher salinity subducts during winter convection to form WNACW.

In this study, we follow McCartney and Talley (1982) and choose the region 24-37°N, 50-70°W as the formation area and pressures less than 1000 m. By defining the depth of this SWT water samples show a discrete T-S distribution with potential densities lower than 26.30 or larger than 26.60 kg/m^3. Besides the potential density constraint, we added the constraint that concentrations of phosphate have to be lower than 0.3 and silicate lower than 3 µmol kg^{-1}.

The properties of WNACW are shown in Figure 4. Besides the linear T-S relationship, a feature of all central waters, another feature of this water mass is, as the alternative name suggests, a potential temperature around18 °C. This is the warmest of the four STWs in the Atlantic Ocean since it has the lowest latitude of formation and is influenced by the high salinity Gulf Stream during formation. Low nutrients, including silicate, phosphate and nitrate are other features compared to other central waters that generally are low in nutrients compared to deeper water masses

3.1.3 Western South Atlantic Central Water (WSACW)

Western South Atlantic Central Water (WSACW) is located in the starting point that central water is transported to the north during the Meridional Overturning Circulation (Kuhlbrodt et al., 2007). For this reason, the importance of WSACW is clear. The WSACW is formed with little directly influence from other central water masses (Stramma and England, 1999), while the origin of other central water masses (e.g. ESACW or ENACW) can, to some extent at least, be traced back to WSACW (Peterson and Stramma, 1991). This water mass is a product of three mode waters mixed together: the Brazil current brings Salinity Maximum Water (SMW) and Subtropical Mode Water (STMW) from the north, while the Falkland Current brings Subarctic Mode Water (SAMW) from the south (Alvarez et al., 2014). Here we follow the work of Stramma and England (1999) and Alvarez et al. (2014) that choose the meeting region of these two currents (25-60°W, 30-45°S) as the formation region of WSACW. We choose potential density (σ_θ) between 26.0 and 27.0 kg/m^3 and salinity higher than 34.5 for defining WSACW. In addition to the physical properties we used the requirement of silicate concentrations lower than 10 µmol kg^{-1} and oxygen concentrations lower than 230 µmol kg^{-1} to define this SWT.

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The temperature distribution in this region indicates another peak in the abundance (histogram) for potential densities higher than 27.0 kg m^{-3}, indicating that the boundary between WSACW and AAIW is at σ_θ = 27.0 kg m^{-3} in this region. The hydrochemical properties of WSACW are shown in Figure 5. Similar to other central waters, WSACW shows a linear T-S relationship with large T and S ranges and low concentration of nutrients, especially low silicate.

3.1.4 Eastern South Atlantic Central Water (ESACW)

The other formation area of SACW in the eastern South Atlantic Ocean is located in area southwest of South Africa. In this region the Agulhas Current brings water from the Indian Ocean (Deruijter, 1982; Lutjeharms and van Ballegooyen, 1988) that meets and mixes with the South Atlantic Current (Gordon et al., 1992; Stramma and Peterson, 1990) from the west. Water mass formed during this process spreads to the northwest and intrudes water from the Benguela Current and enters the subtropical gyre (Peterson and Stramma, 1991). Tracing back to the origin of ESACW, it can be considered as partly originating from WSACW, but since water from Indian Ocean is added by the Agulhas Current we can define WSACW as a new independent STW with characteristic properties.

We choose the meeting region of Agulhas Current and South Atlantic Current (30-40 °S, 0-20 °E) as the formation area of ESACW and display properties of this SWT. To investigate the properties of ESACW, we also follow Stramma and England (1999), and choose 200-700m as the core of this water mass. For the properties, potential density (σ_θ) between 26.00 and 27.20 kg m^{-3} and oxygen concentration between 200 and 240 µmol kg^{-1} are used to define ESACW.

Figure 6a clearly shows the linear T-S relationship for potential density (σ_θ) between 26.00 and 27.20 kg m^{-3}, which is consists with the general property of Central Waters (Alvarez et al., 2014; Emery and Meincke, 1986; Harvey, 1982). As shown in Figure 6b, ESACW exhibits a relative large potential temperature and salinity range and low nutrient concentrations (especially low in silicate) compared to the AAIW below. The properties in ESACW are similar to that of WSACW, although with higher nutrient concentrations due to input from the Agulhas current.

3.2 The Intermediate Layer

The intermediate water masses origins from the upper part of the ocean (i.e. the upper 500m of the water column) but subduct into intermediate depth (1000-1500m) during their formation process. Similarly to the water masses of the central layer, currents in this layer play a significant role to influence the distribution and transport of intermediate water masses. The potential density (σ_θ) of the intermediate water masses usually is between 27.00 and 27.70 kg m^{-3}.

In the Atlantic Ocean we find two main intermediate water masses: SAIW that originates from the north and AAIW that originates from the south, Figure 8. These two water masses are formed in the surface of sub-polar region, and then sink during their way towards the lower latitudes.

Besides AAIW and SAIW here we also define MOW as an intermediate water mass in the north Atlantic since the MOW occupies a similar density range as AAIW and SAIW, although the formation is different. Schematic of main currents in the intermediate layer is shown in Figure 7.

3.2.1 Antarctic Intermediate Water (AAIW)

AAIW is the main water mass in the intermediate depth of the South Atlantic Ocean. This water mass originates from the surface layer (upper 200m) north of the Antarctic Circumpolar Current (ACC) and east of Drake Passage (Alvarez et al., 2014; McCartney, 1982). After formation AAIW subducts and spreads northward along the continental slope of South America (Piola and Gordon, 1989). AAIW can be found through most of the Atlantic Ocean at the depth between 500 and 1200m, below the layer of central water and above the deep waters (Talley, 1996). Two characteristic features of AAIW is low salinity and high oxygen concentration (Stramma and England, 1999).

Based on the work by Stramma and England (1999), we choose the region between 55 and 40°S (east of the Drake Passage) as the formation area of AAIW and look at depths below 200 m so that not only AAIW samples in the formation area but also some samples during the subduction and spreading in the primary stage are considered. As for the boundaries between AAIW and surrounding SWTs, including SACW in the north and NADW in the deep, there are several slightly different definitions. Piola and Georgi (1982) and Talley (1996) define AAIW to have potential densities between 27.00-27.10 and 27.40 kg/m^3. Here however we follow Stramma and England (1999) that define the boundary between AAIW and SACW at σ_θ = 27.00 kg m^{-3} and the boundary between AAIW and NADW at σ_1 = 32.15 kg m^{-3}.

Although the density difference between AAIW and AABW is significant, in the formation areas, there is a direct contact between AAIW and AABW near Drake Strait. Since AABW is easily separated from AAIW on higher silicate concentrations we used silicate concentrations lower than 20 µmol kg^{-1} as a criteria for AAIW. Furthermore we used these criteria in our selection of AAIW: potential density between 26.95 and 27.50 kg m^{-3} and pressure within 300m. More criteria are required to identify AAIW with neighboring SWTs, since the formation area of AAIW is bordered with WSACW in the north and AABW in the south. High oxygen (> 230 µmol kg^{-1}) is the important sign that distinguishes AAIW from Central Waters (WSACW and ESACW), while relative high potential temperature (>-0.5 °C) and low silicate (< 30 µmol kg^{-1}) are differentiated standards between AAIW and AABW. As shown in Figure 8, most of the AAIW samples have a potential density between σ_θ = 27.00-27.40 kg m^{-3}; the few exceptions still adhere to the boundary $\sigma_1 < 32.15$ kg m^{-3}. The characteristics of AAIW show low salinity, high oxygen and low silicate concentrations compared to SACW and NADW, and low silicate concentration.

3.2.2 Subarctic Intermediate Water (SAIW)

Subarctic Intermediate Water (SAIW) originates from the surface layer of the western boundary of the North Atlantic Subpolar Gyre, along the Labrador Current (Lazier and Wright, 1993; Pickart et al., 1997). This SWT subducts and spreads southeast in the region north of the NAC, advects across the MAR and finally interacts with MOW, that comes from the eastern Atlantic below ENACW (Arhan, 1990; Arhan and King, 1995). The formation of SAIW is mixture of two surface water types: Water with high temperature and salinity carried by the NAC and cold and fresh water from the Labrador Current (Garcia-Ibanez et al., 2015; Read, 2000). In Garcia-Ibanez et al. (2015), there are two definitions of SAIW, SAIW$_6$, which is biased to the warmer and saltier NAC, and SAIW$_4$, which is closer to the cooler and fresher Labrador Current. In this study we discuss the combination of these two end-members when considering the whole Atlantic Ocean scale.

For the spatial boundaries we follow Arhan (1990) and choose longitudes between 35 and 55°W, and latitudes between 50 and 60 °N, i.e. the region along the Labrador Current and north of the NAC as the formation area of SAIW (Figure 9a). Within this area we follow Read (2000), and choose potential densities higher than 27.65 kg m^{-3} and potential temperature higher than 4.5 °C to define SAIW. Similar to the definition of AAIW, we include samples in the depth range from the MLD to 500m as the core layer of SAIW; this pressure includes formation and subduction of SAIW.

In the T-S relationship (Figure 9b), the mixing of two main sources, the warmer and saltier NAC and the colder and fresher Labrador Current, is evident. In Figure 9c we can see that this SWT is characterized by relative low potential temperature, salinity and silicate concentration but is high in oxygen

3.2.3 Mediterranean Overflow Water (MOW)

The predecessor of the Mediterranean Overflow Water (MOW) is Mediterranean Waters flowing out through the Strait of Gibraltar whose main component is modified Levantine Intermediate Water. This is a SWT characterized by high salinity and temperature and intermediate potential density in the Northeast Atlantic Ocean (Carracedo et al., 2016). After passing the Strait of Gibraltar, the Mediterranean water mixes rapidly with the overlying ENACW leading to a sharp decrease of salinity and potential density (Baringer and Price, 1997). In Gulf of Cadiz, the outflow of MOW turns into two branches: One branch continues to the west, descending the continental slope, mixing with surrounding water masses in the intermediate depth and influence the water mass composition as far west as the MAR (Price et al., 1993). The other branch spreads northwards along the coast of Iberian peninsula and along the European coast and its influence can be observed as far north as the Norwegian Sea (Reid, 1978, 1979).

Here we follow Baringer and Price (1997) and consider MOW to be represented by the high salinity (salinity between 36.35 and 36.65) samples west of the Strait of Gibraltar as a SWT in the Northeast Atlantic (Figure 10) although the Mediterranean waters in the Strait are characterized by salinity higher than 38.4).

Almost the entire Northeast Atlantic, east of the MAR, intermediate layer is influenced by MOW. As the most characteristic property of MOW is the high salinity, we display a salinity section plot (Figure 10d) of A05 cruise from 2005 (74AB2005050), where the high salinity of MOW can be seen and how the high salinity core erodes westward towards the MAR. The high potential temperature and salinity compared to other water samples at same depth, and the characteristically low and nutrient concentrations are evident in Figure 10b. Due to the limited number of samples (less than 200) within our definition of MOW in GLODAPv2, we refrain from showing the histogram. The properties of MOW can be seen in Figure 10 and Table 3.

3.3 The Deep and Overflow Layer

To the deep and overflow water masses belongs those below the Intermediate Layer, approximately from 1500 to 4000m, with potential densities between 27.7 and 27.88 kg m^{-3}. Relative high salinity in the deep (compared to the intermediate and bottom waters) is another significant property. The source region of these waters is confined to the North Atlantic, the formation areas and main currents in this layer are shown in Figure 11. The southward flow of NADW in the North Atlantic, as well as northward flow of AABW in the South Atlantic are indispensable components of Atlantic Meridional Overturning Circulation (AMOC) (Lynch-Stieglitz et al., 2007) (Broecker and Denton, 1989; Elliot et al., 2002).

The North Atlantic Deep Water (NADW) is the main water mass in this layer. NADW is mainly formed in the Labrador Sea and Irminger Basin in relative high latitude region in North Atlantic by mixing of Labrador Sea Water and the two variations of overflow waters; ISOW and DSOW. We make a distinction of upper and lower NADW, the upper portion origins from LSW and lower portion origins from ISOW and DSOW. From the formation area, NADW spreads to the south mainly with the Deep Western Boundary Current (DWBC) (Dengler et al., 2004), through the most Atlantic Ocean until ~50 °S where it meets Antarctic Circumpolar Current. During the south way along DWBC, NADW also spreads significantly in the zonal direction, so that we can find NADW in the whole Atlantic basin at these densities (Lozier, 2012).

Both Denmark Strait Overflow Water (DSOW) and Iceland-Scotland Overflow water (ISOW) originate from Arctic Ocean and the Nordic Seas. In North Atlantic, these two water masses sink and flow west and east of Iceland respectively, and finally, they meet and mix with each other in the Irminger Basin (Stramma et al., 2004; Tanhua et al., 2005). As two main contributions to the formation of lower portion of NADW, they play a significant role in AMOC. Here we show our analysis based on GLODAPv2 database and discuss DSOW and ISOW separately.

3.3.1 Labrador Sea Water (LSW)

As an important water mass by its own virtue and for the formation of North Atlantic Deep Water (NADW), LSW is predominant in mid-depth (between 1000m and 2500m depth) in the Labrador Sea region (Elliot et al., 2002). LSW is characterized by relative low salinity (lower than 34.9) and high oxygen concentration (~290 µmol kg^{-1}) (Talley and Mccartney, 1982). Another important criterion of LSW is the potential density (σ_θ), that ranges from 27.68 to 27.88 kg m^{-3} (Clarke and Gascard, 1983; Gascard and Clarke, 1983; Kieke et al., 2006; Stramma et al., 2004). In the large spatial scale, LSW can be considered as one water mass (Dickson and Brown, 1994), however significant differences of different "vintages" of LSW exitst (Kieke et al., 2006; Stramma et al., 2004). LSW can broadly be divided into upper Labrador Sea Water (uLSW) and classic Labrador Sea Water (cLSW) with the boundary between them at potential density of 27.74 kg m^{-3} (Kieke et al., 2007; Kieke et al., 2006; Smethie and Fine, 2001).

The following results show our analysis based on GLODAPv2 in the Labrador Sea and Irminger Basin, west of Mid-Atlantic-Ridge. For the purpose of our analysis (the whole scale of the Atlantic Ocean) we consider LSW as one integral water mass. Although the Labrador Sea is located in North Atlantic between the Labrador Peninsula and Greenland, for this analysis we consider the formation region of LSW (Figure 12a). Within this geographical region we follow the definition from Clarke and Gascard (1983) and Stramma and England (1999), defining LSW as samples with potential density (σ_θ) between 27.68 to 27.88 kg m^{-3} (Figure 12b) in the depth range of 500-2000m (Elliot et al., 2002).

Obvious characteristics of LSW are relative low salinity and high oxygen concentration is obvious. Figure 12c shows the histogram of all samples that we consider to represent LSW in this analysis. The relatively large spread in properties is indicative of the different "vintages" of LSW, in particular the bi-modal distribution of density, and partly for oxygen.

3.3.2 Denmark Strait Overflow Water (DSOW)

In North Atlantic, a number of water masses from the Arctic Ocean and the Nordic Seas flows through Denmark Strait west of Iceland. At the sill of the Denmark Strait and during the descent into the Irminger Sea these water masses undergo intense mixing. Here we use samples from the Irminger Sea with potential density higher than 27.88 kg m^{-3} (Tanhua et al., 2005) for our definition of DSOW. In addition we require the silicate concentration to be lower than 11 µmol kg^{-1} to distinguish DSOW from NEABW, which has a high silicate concentration.

As shown in Figure 13b DSOW is mostly found close to the bottom between 2000 and 4000m, as expected for an overflow water. In addition to the high density and low temperature DSOW also has high oxygen concentration (~ 290-310 µmol kg^{-1}).

3.3.3 Iceland-Scotland Overflow Water (ISOW)

The Iceland Scotland Overflow Water, ISOW, flows from the Iceland Sea to the North Atlantic in the region east of Iceland, mainly through the Faroe-Bank Channel close to the bottom. ISOW flows and turn into two main branches when passing the Charlie-Gibbs Fracture Zone (CGFZ). The first one flows through the Mid-Atlantic-Ridge, into the Irminger basin, meets and mixes with DSOW there, and finally joins the lower portion of NADW. The other branch goes southward and mixes with Northeast Atlantic Bottom Water (NEABW) (Garcia-Ibanez et al., 2015). The pathway of ISOW closely follows the Mid-Atlantic-Ridge in the Iceland Basin where also NEABW could be found, characterized by high nutrient and low oxygen concentration. In order to safely distinguish ISOW from LSW in the region west of MAR, we define ISOW as samples with salinity higher than 34.95, potential density higher than 27.83 kg m^{-3}. Figure 14 displays our characterization of ISOW based on GLODAPv2 in the Iceland Basin, which is consistent from the result in the literature (Garcia-Ibanez et al., 2015).

3.3.4 Upper North Atlantic Deep Water (uNADW)

The uNADW is formed by mixing of mainly ISOW and LSW and we consider this to be a distinct water mass just south of the Labrador Sea as this region is identified as the formation area of upper and lower NADW (Dickson and Brown, 1994).

We select the region between latitude 40 and 50°N, west of the MAR as the formation area of NADW (Figure 15b) and use the criteria of potential density between 27.72 and 27.82 kg m^{-3} with depth range from 1200 to 2000m to define the upper NADW (Stramma et al., 2004).

As a product of mixing from LSW and ISOW, upper NADW inherits main properties from LSW but also contains some of characteristics from ISOW. Relative low salinity and high salinity is still significant features of uNADW. However, as shown in Figure 15d, relatively increased salinity and decreased oxygen concentration can be found due to the impact from ISOW. Furthermore, ISOW also brings slight increase of nutrients including silicate, phosphate and nitrate.

3.3.2 Lower North Atlantic Deep Water (lNADW)

We select water samples from the same geographic region as upper NADW to define the lower NADW. Below the uNADW in this region, ISOW and DSOW (with influence of LSW) mix with each other and form the lower portion of NADW (Stramma et al., 2004). We use water samples found at depths between 2000 and 3000 m with potential densities between 27.76 and 27.88 kg m^{-3} to define lower NADW.

From the data shown on Figure 16d, we can see lower NADW has properties more inclined to ISOW compared with DSOW. For instance, values of salinity and oxygen concentration are between ISOW and DSOW but obviously closer to ISOW. The nutrients, lower NADW have almost the same values to ISOW, further verified this inference. High potential temperature shows that the impact from LSW to lower NADW cannot be ignored.

3.4 The Bottom Layer

We define bottom waters as the densest water masses that occupy the lowest layers of the water column, typically below 4000 m depth and with potential densities higher than 27.88 kg m^{-3}. These water masses have an origin in the Southern Ocean (Figure 17) and are also characterized by their high silicate concentrations (higher than 100 µmol kg^{-1}), in addition to the high densities.

Antarctic Bottom Water (AABW) is the main water mass in the bottom layer, and is formed in the Weddell Sea region, south of Antarctic Circumpolar Current (ACC) through mixing of Circumpolar Deep Water (CDW) and Weddell Sea Bottom Water (WSBW) (van Heuven et al., 2011). After the formation, AABW spreads to the north across the equator and further northwards until ~40 °N, where we define this water mass as North East Atlantic Bottom Water (NEABW).

3.4.1 Antarctic Bottom Water (AABW)

Antarctic Bottom Water (AABW) is the main bottom water in the South Atlantic Ocean and is also an important bottom water mass in the North Atlantic. As one of the important components in Atlantic Meridional Overturning Circulation (AMOC), AABW spreads northward below 4000m depth, mainly west of Mid-Atlantic-Ridge (MAR) and plays a significant role in the Thermohaline Circulation (Andrié et al., 2003; Rhein et al., 1998). The origin of AABW in Atlantic section can be traced back to the Weddell Sea as a product of mixing of Weddell Sea Bottom Water (WSBW) and Circumpolar Deep Water (CDW) (Alvarez et al., 2014; Foldvik and Gammelsrod, 1988).

The definition of AABW is all water samples formed south of the Antarctic Circumpolar Current (ACC), i.e. south of 63°S in the Weddell Sea, with neutral density (γ) larger than 28.27 kg m^{-3} (Orsi et al., 1999; Weiss et al., 1979). As an additional constraint we define AABW as water samples with silicate higher than 120 µmol kg^{-1} to distinguish AABW from other water masses in this region as high silicate is a trade mark characteristic of AABW. The main source region of AABW is the Weddell Sea.

In Figure 18, we can see clearly that there are two main original water masses (red points) in the selected formation area of AABW (blue points). This result is also consistent with Orsi et al. (1999) and van Heuven et al. (2011). The first water mass is the relative warm (θ>0 °C) remnants from CDW, which comes with the ACC from the north. The other one, which is the extremely cold Shelf Water (θ<-1.0°C) comes as Weddell Sea Bottom Water (WSBW) from the south. As shown in Figure 18 we find AABW from 1000m to 5500m depth.

The characterisitc properties of AABW is the low temperature (θ<0 °C), salinity (<34.68) and high nutrient concentration, especially the high silicate concentrations. In Figure 17c we can see a relative complex distribution of potential temperature, probably due to the mixing between different water masses with quite different temperatures (warm CDW and cold shelf water) that forms AABW.

3.4.2 Northeast Atlantic Bottom Water (NEABW)

Northeast Atlantic Bottom Water (NEABW), also called lower Northeast Atlantic Deep Water (lNEADW in Garcia-Ibanez et al. (2015)), is mainly found below 4000m depth in the eastern basin of the North Atlantic. This water mass is an extension of AABW during the way to the north, since the characteristics of AABW changes significantly on the slow transport north we choose to define this as a new water mass north of the Equator, similar to the formation of NADW south of the Labrador Sea.

To define we choose the region east of the MAR and between the equator and 30 °N, i.e. before NEABW enters the Iberian Basin, as the formation area (Figure 19). We also use the criteria of water samples from a depth deeper than 4000m and potential temperature above 1.8 °C. In the T-S diagram of NEABW (Figure 19) we can see the linear T-S relationship similar to AABW in the Weddell Sea, but with significantly higher potential temperatures and salinities, roughly 1.95 °C and 34.887, respectively. Most NEABW samples have a potential density higher than 27.88 kg m^{-3} and NEABW is characterized by low potential temperature (θ), low salinity but high silicate concentration. This shows that NEABW originates from AABW, although most properties have been changed significantly from the South Atlantic.

3.4.3 Circumploar Deep Water (CDW) / Warm Deep Water (WDW)

Circumpolar Deep Water (CDW) or, as it is also called, Warm Deep Water (WDW), is the lighter of the two SWTs that constitutes AABW. In our study we consider water mass that mixes with WSBW directly as CDW (WDW in van Heuven et al. (2011)) and the region between 55 and 65 °S as the formation area. The origin of CDW can be tracked to the southward flow of NADW. At about 50°S NADW is deflected upward by AABW before reaching the ACC area, this NADW mixes with other water masses in ACC and forms a new water mass called CDW. Then CDW flows further southward and passes the ACC.

To specify CDW we selected water samples with from depth between 200 and 1000m in the region east of 60°W between 55 and 65°S as the core of CDW. We also placed the additional constraints of having salinity lower than 34.64 and potential density higher than 27.80 kg m^{-3}. The properties of CDW are shown in Figure 20. Similar to other bottom SWTs, CDW is characterized by high nutrient concentrations (silicate, phosphate and nitrate) and low oxygen concentration. The potential temperature of CDW is between 0 and 1 °C while the potential density is larger than 27.8 kg m^{-3}, and the salinity higher than 34.63.

3.4.4 Weddell Sea Bottom Water (WSBW)

The Weddell Sea Bottom Water (WSBW) is the denser SWT that takes part in the formation of AABW. Similar to CDW, WSBW is also formed in the Weddell Sea region, relative warm water (σ_θ > 0 °C) flows southward and cools down to σ_θ lower than -1°C by mixing with extremely cold shelf water that is transported down along

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the continental slope. WSBW is thus formed in the Weddell Sea basin below the depth of 3000m, before it meets and mixes with CDW/WDW. Compared with CDW, its low potential temperature is a significant property of WSBW (van Heuven et al., 2011).

We follow van Heuven et al. (2011) and choose water samples in the latitudinal boundaries of 55 - 65 °S in the Weddell Sea with pressures larger than 3000 m as the formation core area. We additionally constrain our selection to samples with potential temperature lower than -0.7 °C and silicate higher than 105 µmol/kg. The properties of WSBW are shown in Figures 21a and b. In addition to the physical properties, such as low potential temperature and high potential density, WSBW has high nutrient concentrations, but dislike CDW, WSBW has high oxygen concentration.

4. Discussion

We have defined Atlantic Ocean Water Masses (WMs) in their formation area as source water types (SWTs) in a 7-dimensional hydrochemical space. The properties of SWTs are important since this is the fundamental basis to label and investigate water mass transport, distribution and mixing. Table 3 provides an overview of the properties, and the standard deviation, of the 16 Atlantic Ocean SWTs considered in this study. We used seven often measured hydrochemical and physical variables to characterize 16 main SWTs in the Atlantic Ocean. To guide the water mass descriptions we divided the distribution of SWTs into four main vertical layers roughly separated by potential density in the shallow and concentration of silicate in the deep southern Hemisphere. The upper layer (σ_Θ<27.00 kg m^{-3}) occupies the most shallow layer (typically down to about 500 m depth) of the ocean below the mixed layer, that we do not consider in this analysis. The upper layer is occupied by central waters: ENACW, WNACW, WSACW and ESACW, mainly characterized by relative high potential temperature and salinity. The intermediate layer is situated between the upper layer and the deep layer at roughly 1000 and 2000m depth. Of the three SWTs in this layer, AAIW and SAIW are both characterized have relative low salinity and temperature, while the MOW has high salinity and temperature. In the deep and overflow layer between roughly 2000 and 4000m we find SWTs with an origin in the north Atlantic. The bottom layer is occupied by SWTs with a southern origin; these are very cold SWTs with high densities and silicate concentrations.

In Figure 22 we show an overview of the position of the SWTs in a Salinity-Temperature plot where we plotted the SWTs from the different layers in different colors. It is obvious that a range of additional variables other than temperature and salinity is helpful, if not necessary, to reliable distinguish different water masses from each other, and to calculate the mixing ratios of water masses in a water sample with a particular characteristic.

The here presented characteristics and (property value and the standard deviation) of Atlantic Ocean SWTs is intended to guide water mass analysis of hydrographic data.

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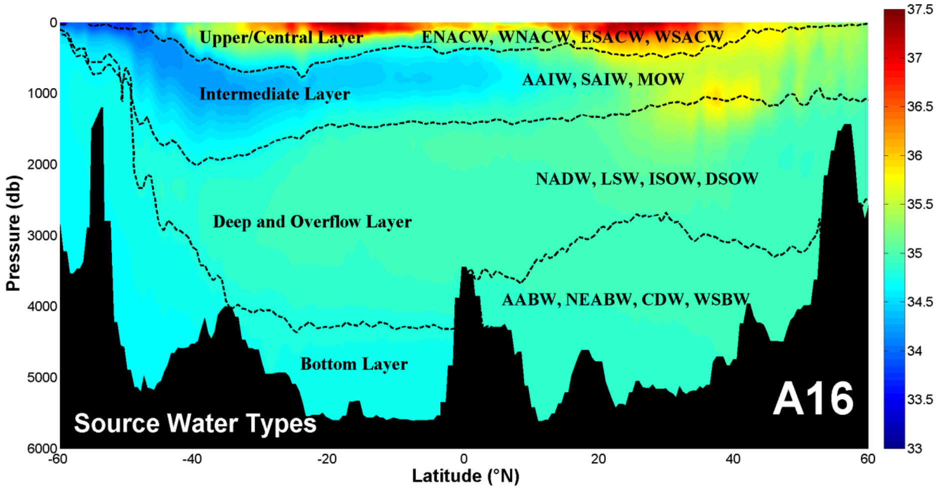

Figure 1: Salinity section from the A16 GO-SHIP cruises in 2013

(Expocode 33RO20130803 in North Atlantic & 33RO20131223 in South Atlantic)

The dashed lines show the four vertical layers divided by potential density except for the boundary between the deep and bottom layers in the south hemisphere which is based on the concentration of silicate.

635

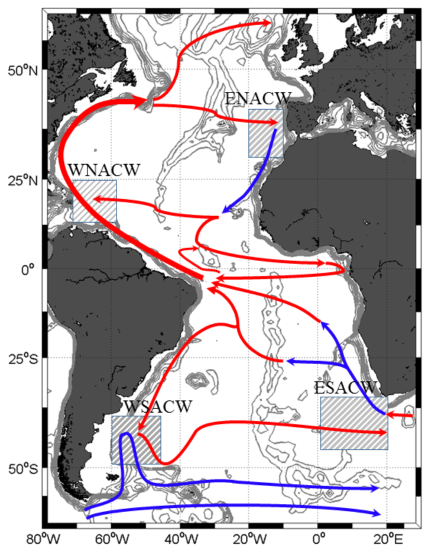

Figure 2: The water mass formation areas and the schematic of main currents (Warm currents in red and cold currents in blue) in the Upper Layer.

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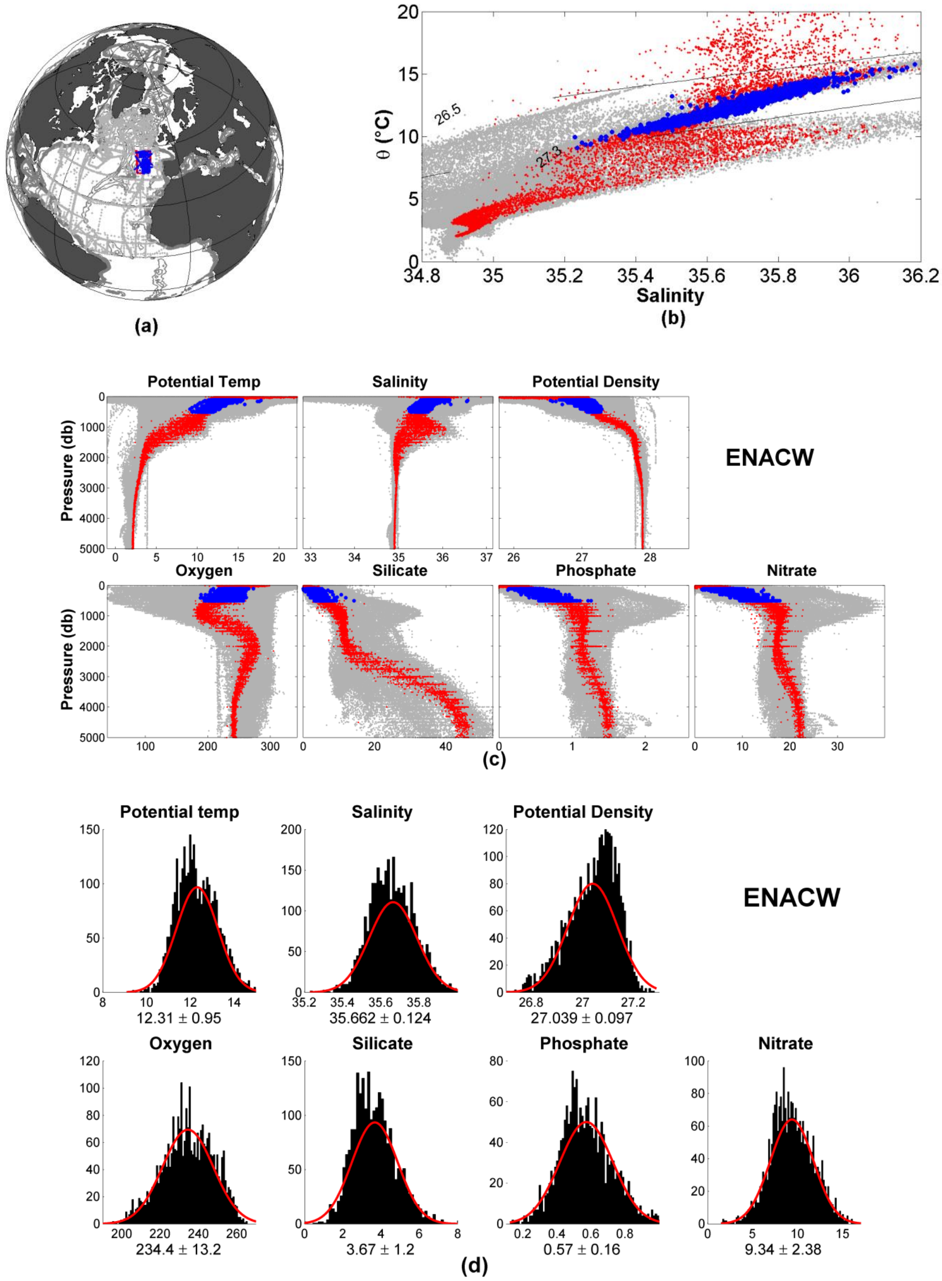

Figure 3: Overview of Eastern North Atlantic Central Water (ENACW):

Panel a) shows the formation area used to define the water mass, panel b) show a T-S diagram and panel c) the distribution of key properties vs. pressure. In panel d) we show bar plots of the data distribution of samples used to define the water mass. Potential Temperature in (°C), Potential Density in kg/m^3, Oxygen and nutrients in µmol/kg^3. The red Gaussian fit shows mean and σ based on selected data.

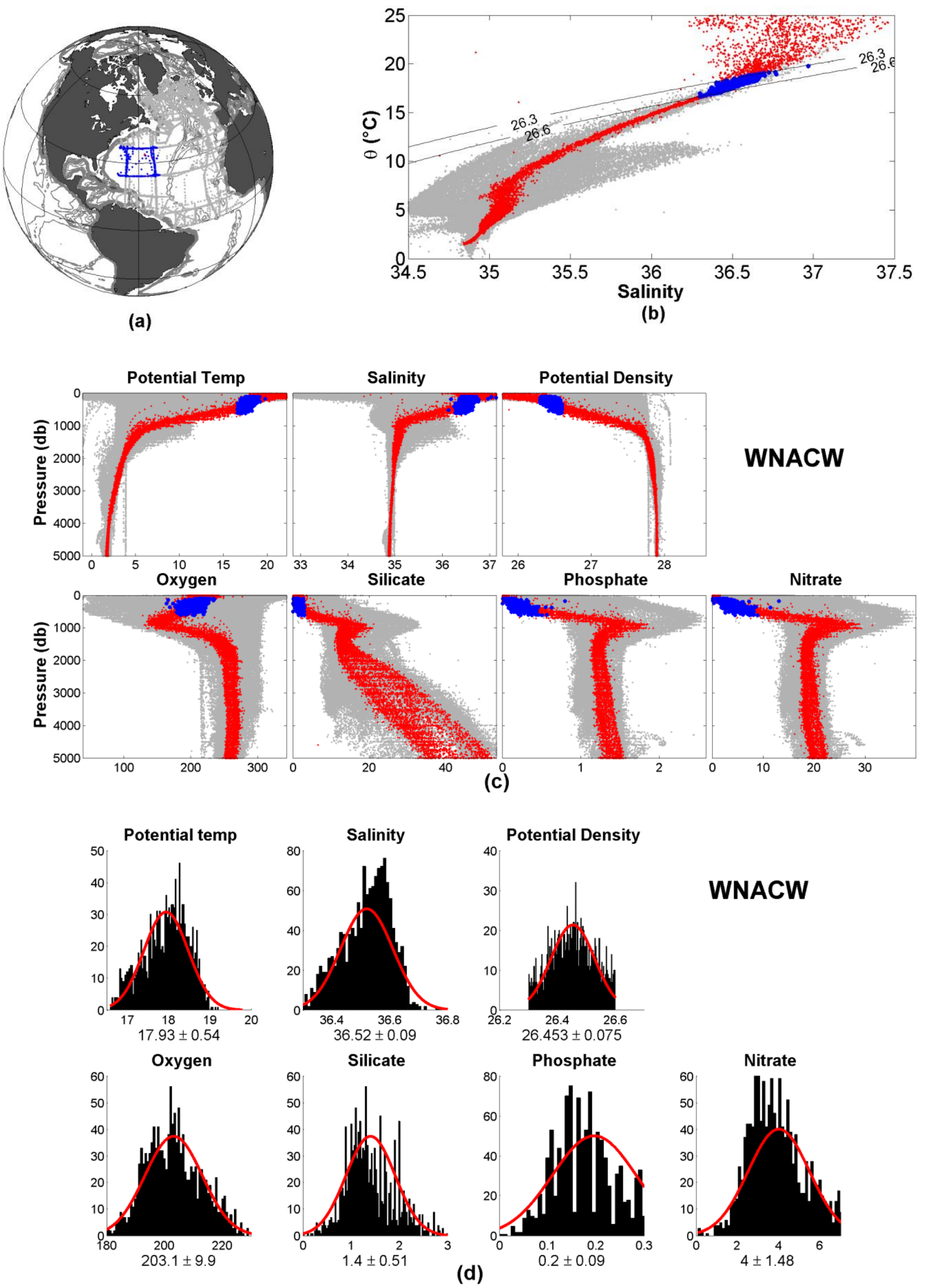

Figure 4: Overview of Western North Atlantic Central Water (WNACW):

Panel a) shows the formation area used to define the water mass, panel b) show a T-S diagram and panel c) the distribution of key properties vs. pressure. In panel d) we show bar plots of the data distribution of samples used to define the water mass. Potential Temperature in (°C), Potential Density in kg/m^3, Oxygen and nutrients in µmol/kg^3. The red Gaussian fit shows mean and σ based on selected data.

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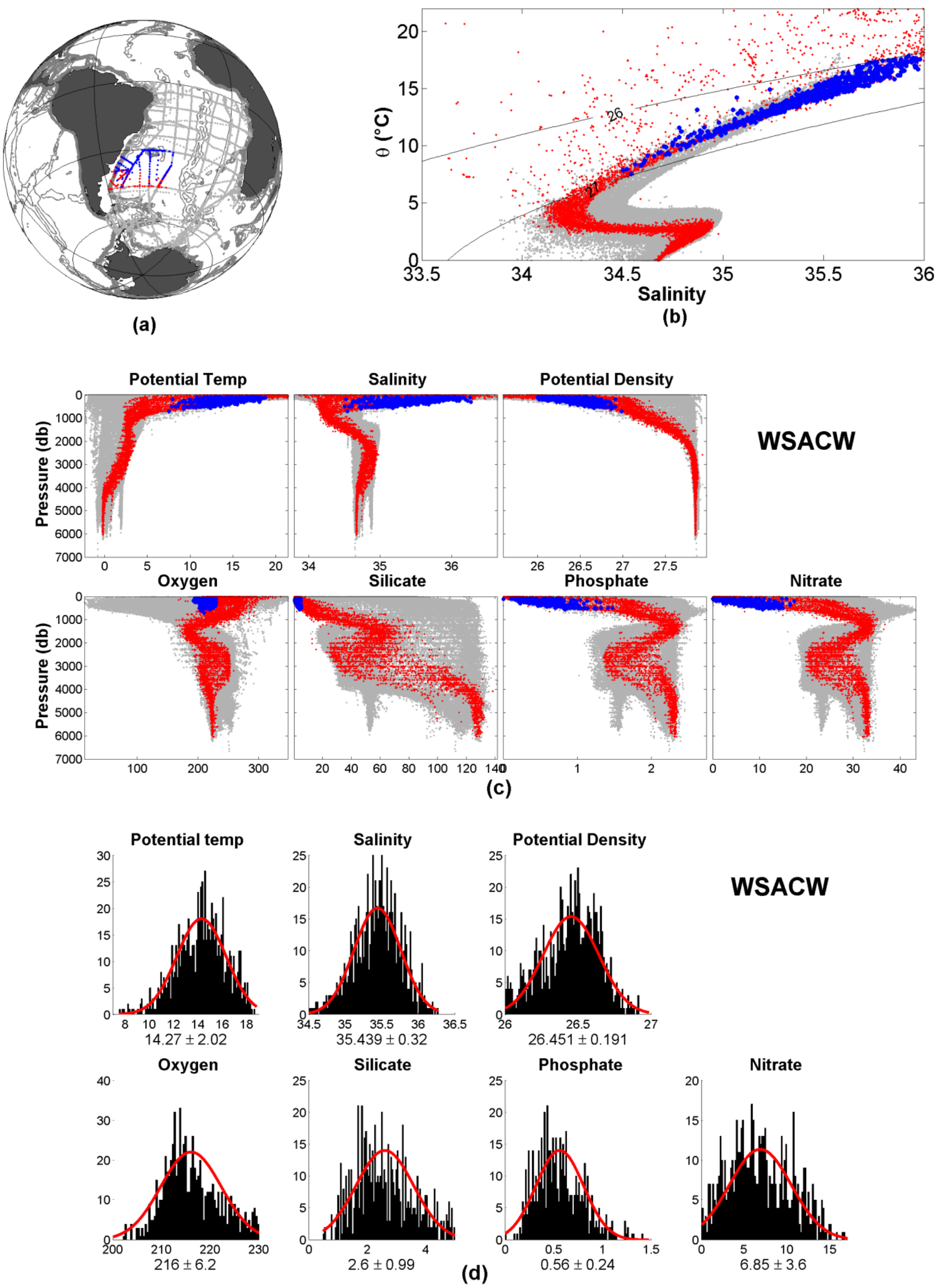

Figure 5: Overview of Western South Atlantic Central Water (WSACW):

Panel a) shows the formation area used to define the water mass, panel b) show a T-S diagram and panel c) the distribution of key properties vs. pressure. In panel d) we show bar plots of the data distribution of samples used to define the water mass. Potential Temperature in (°C), Potential Density in kg/m^3, Oxygen and nutrients in μmol/kg^3. The red Gaussian fit shows mean and σ based on selected data.

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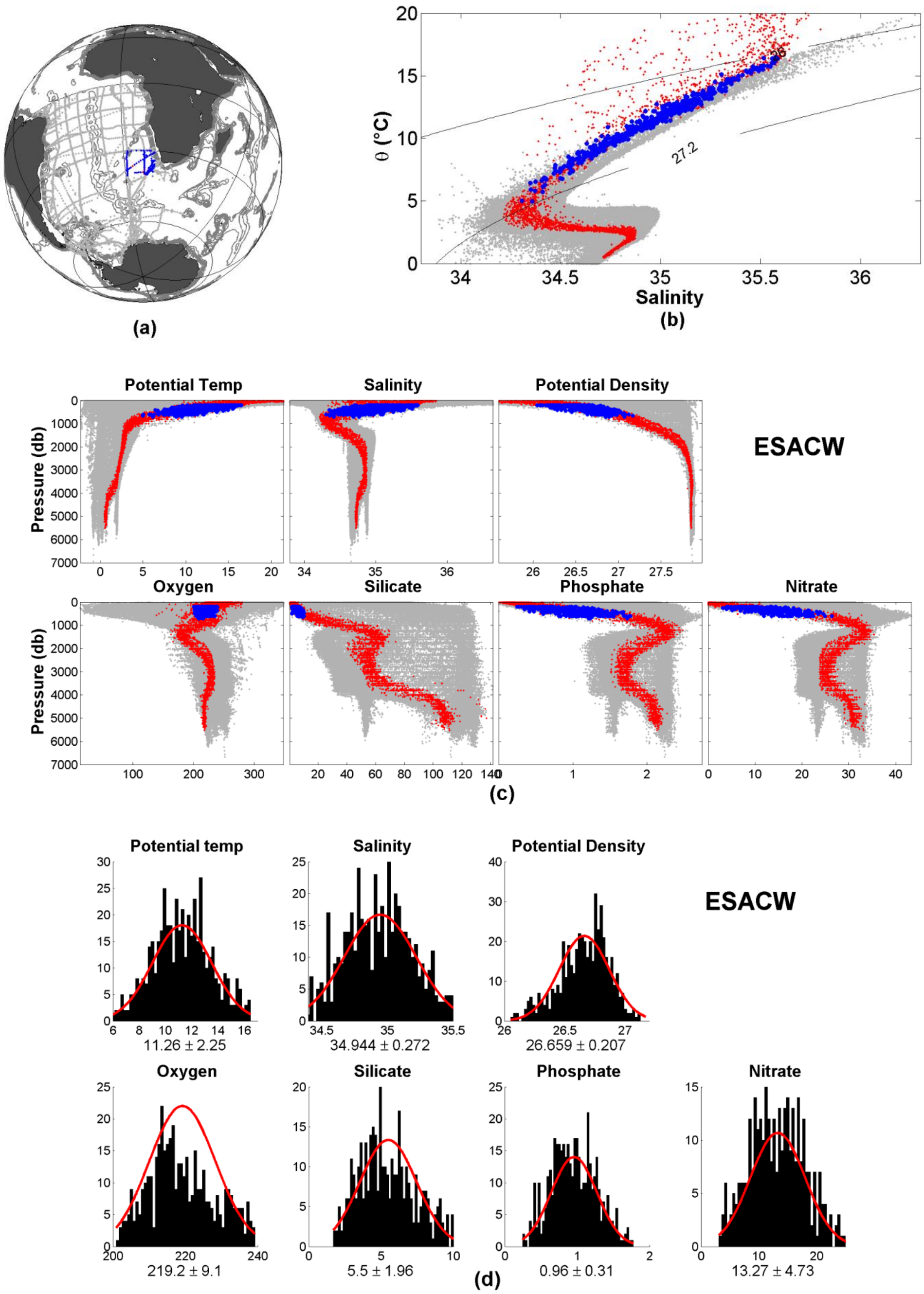

Figure 6: Overview of Eastern South Atlantic Central Water (ESACW):

Panel a) shows the formation area used to define the water mass, panel b) show a T-S diagram and panel c) the distribution of key properties vs. pressure. In panel d) we show bar plots of the data distribution of samples used to define the water mass. Potential Temperature in (°C), Potential Density in kg/m^3, Oxygen and nutrients in µmol/kg^3. The red Gaussian fit shows mean and σ based on selected data.

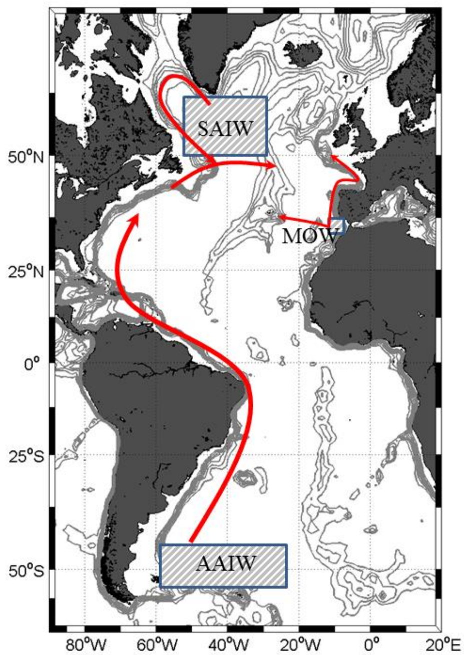

Figure 7: The water mass formation areas and the schematic of main currents in the Intermediate Layer

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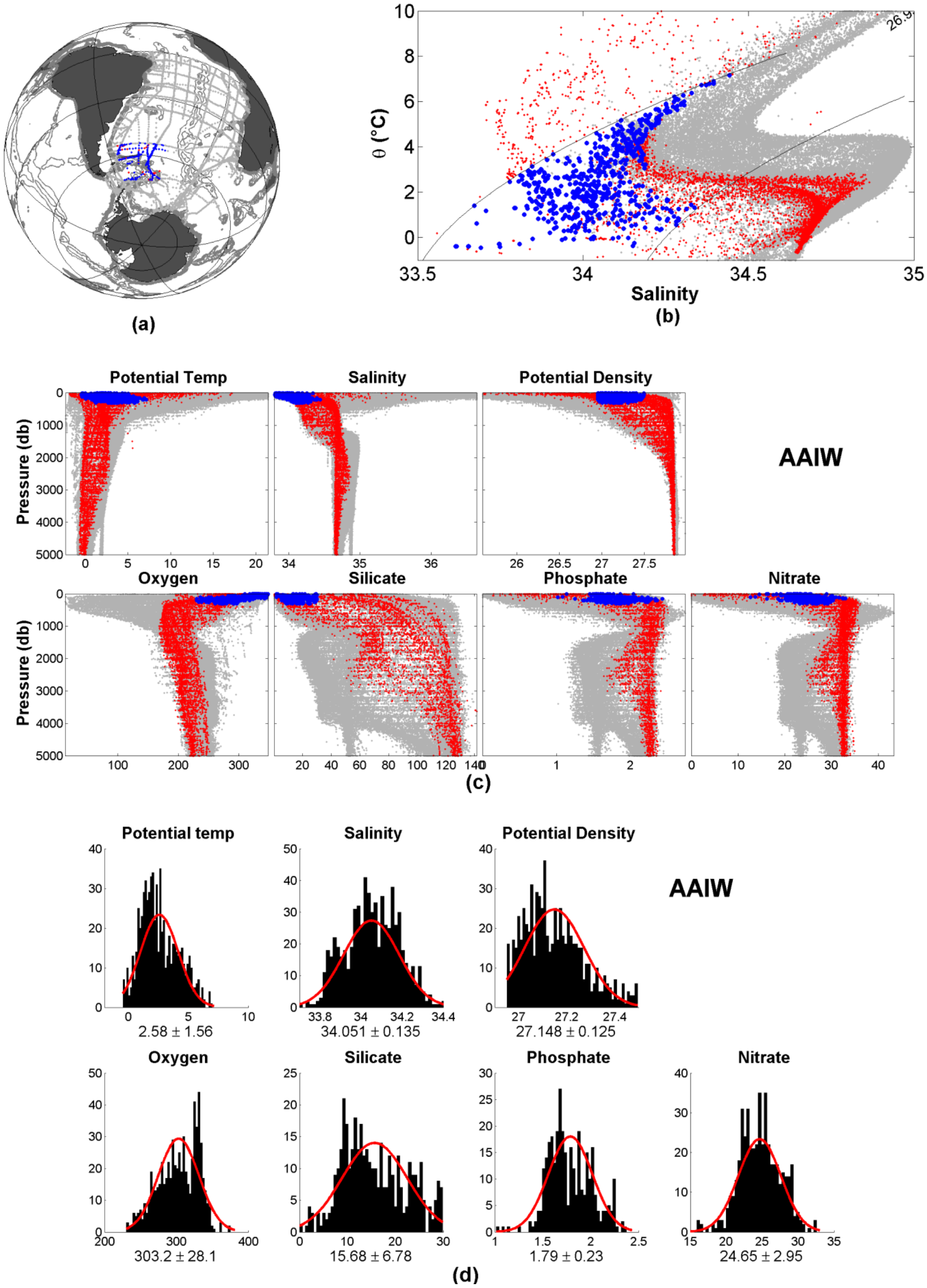

Figure 8: Overview of Antarctic Intermediate Water (AAIW):

Panel a) shows the formation area used to define the water mass, panel b) show a T-S diagram and panel c) the distribution of key properties vs. pressure. In panel d) we show bar plots of the data distribution of samples used to define the water mass. Potential Temperature in (°C), Potential Density in kg/m^3, Oxygen and nutrients in µmol/kg^3. The red Gaussian fit shows mean and σ based on selected data.

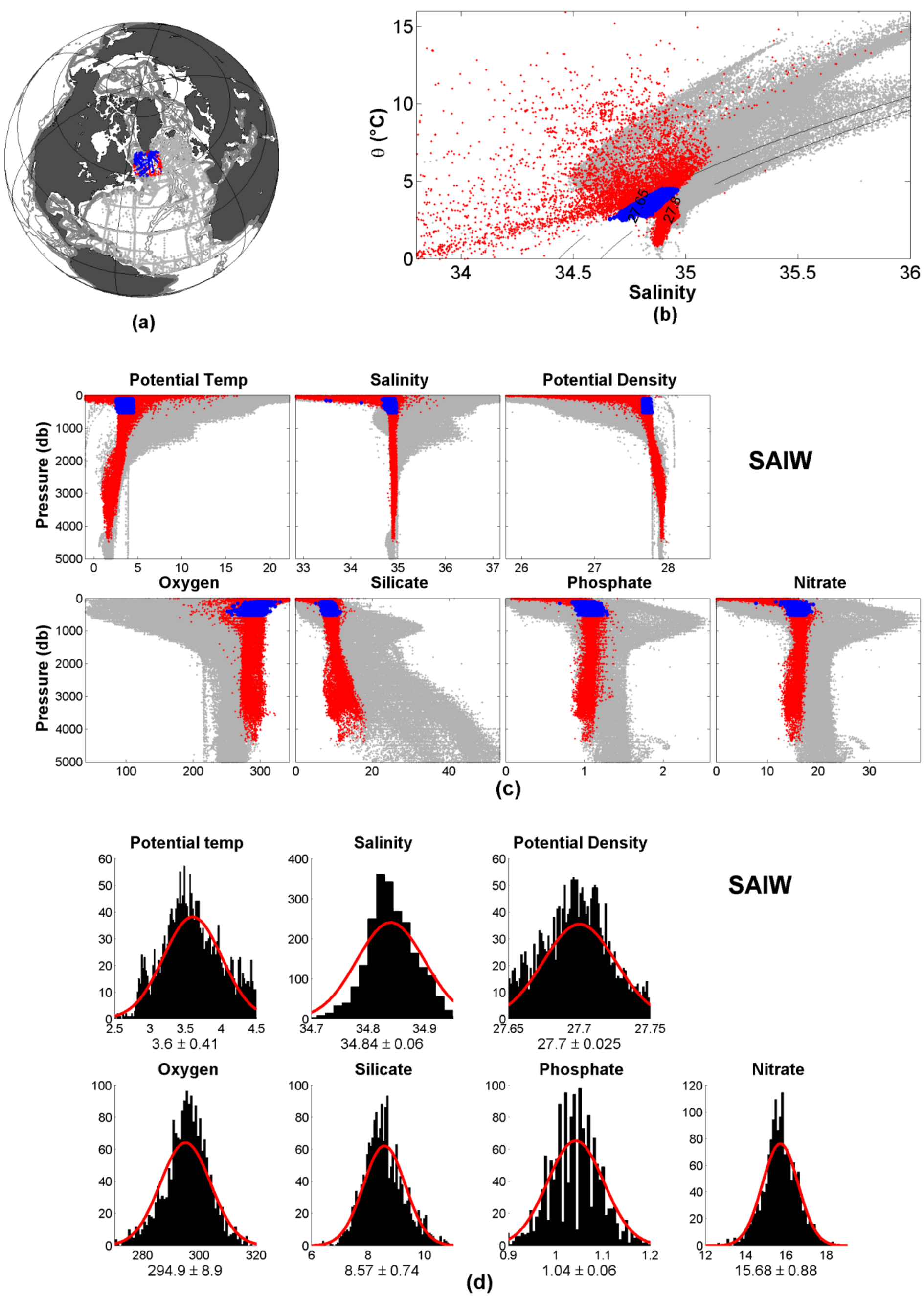

Figure 9: Overview of Subarctic Intermediate Water (SAIW):

Panel a) shows the formation area used to define the water mass, panel b) show a T-S diagram and panel c) the distribution of key properties vs. pressure. In panel d) we show bar plots of the data distribution of samples used to define the water mass. Potential Temperature in (°C), Potential Density in kg/m^3, Oxygen and nutrients in µmol/kg^3. The red Gaussian fit shows mean and σ based on selected data.

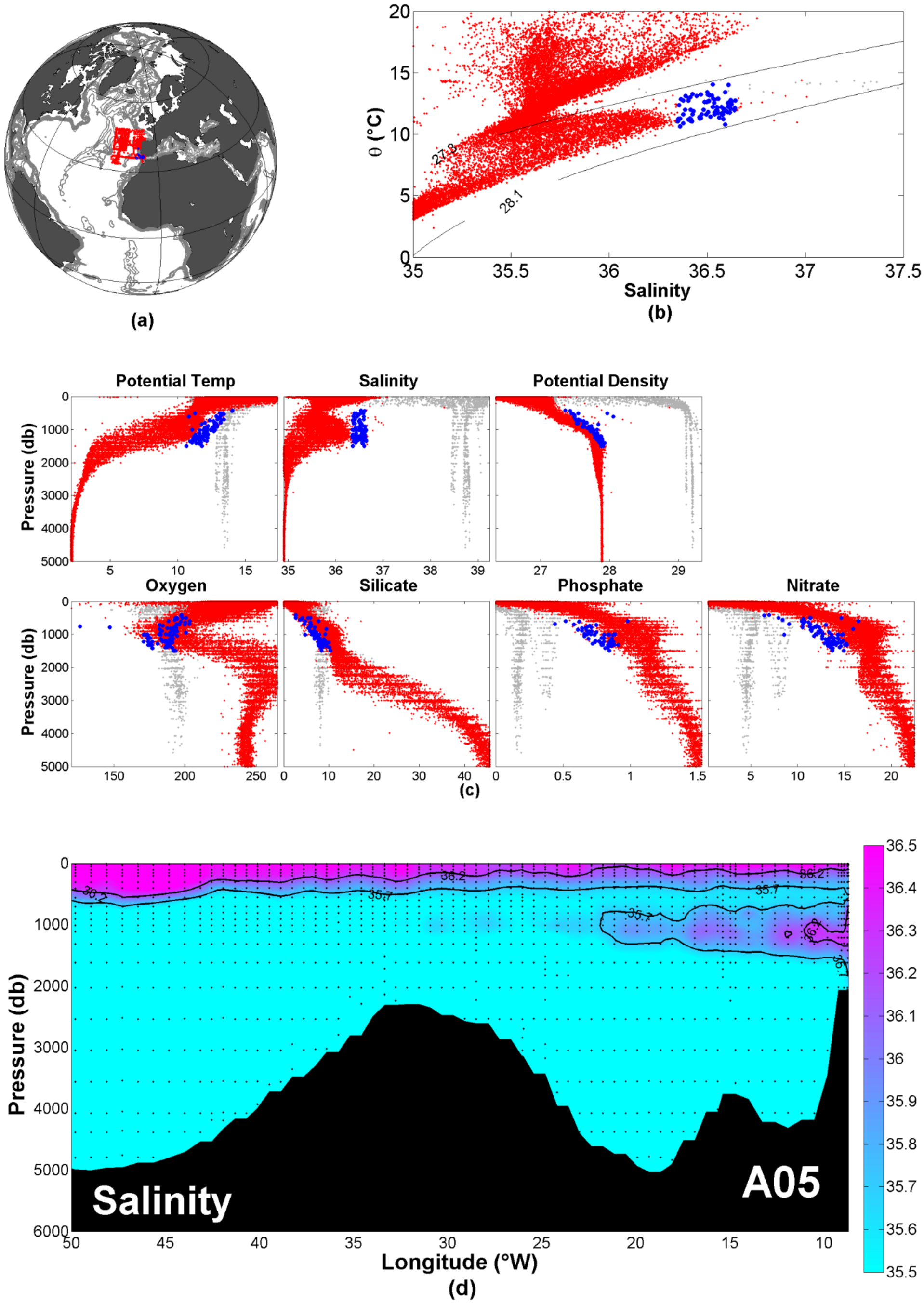

Figure 10: Overview of Mediterranean Overflow Water (MOW):

Panel a) shows the formation area used to define the water mass, panel b) show a T-S diagram and panel c) the distribution of key properties vs. pressure. In panel d) we show the salinity along A05 cruise.

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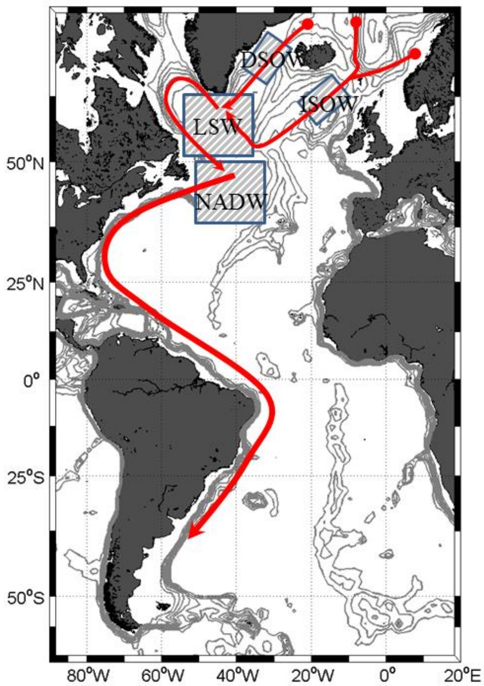

Figure 11: The water mass formation areas and the schematic of main currents in the Deep and Overflow Layer.

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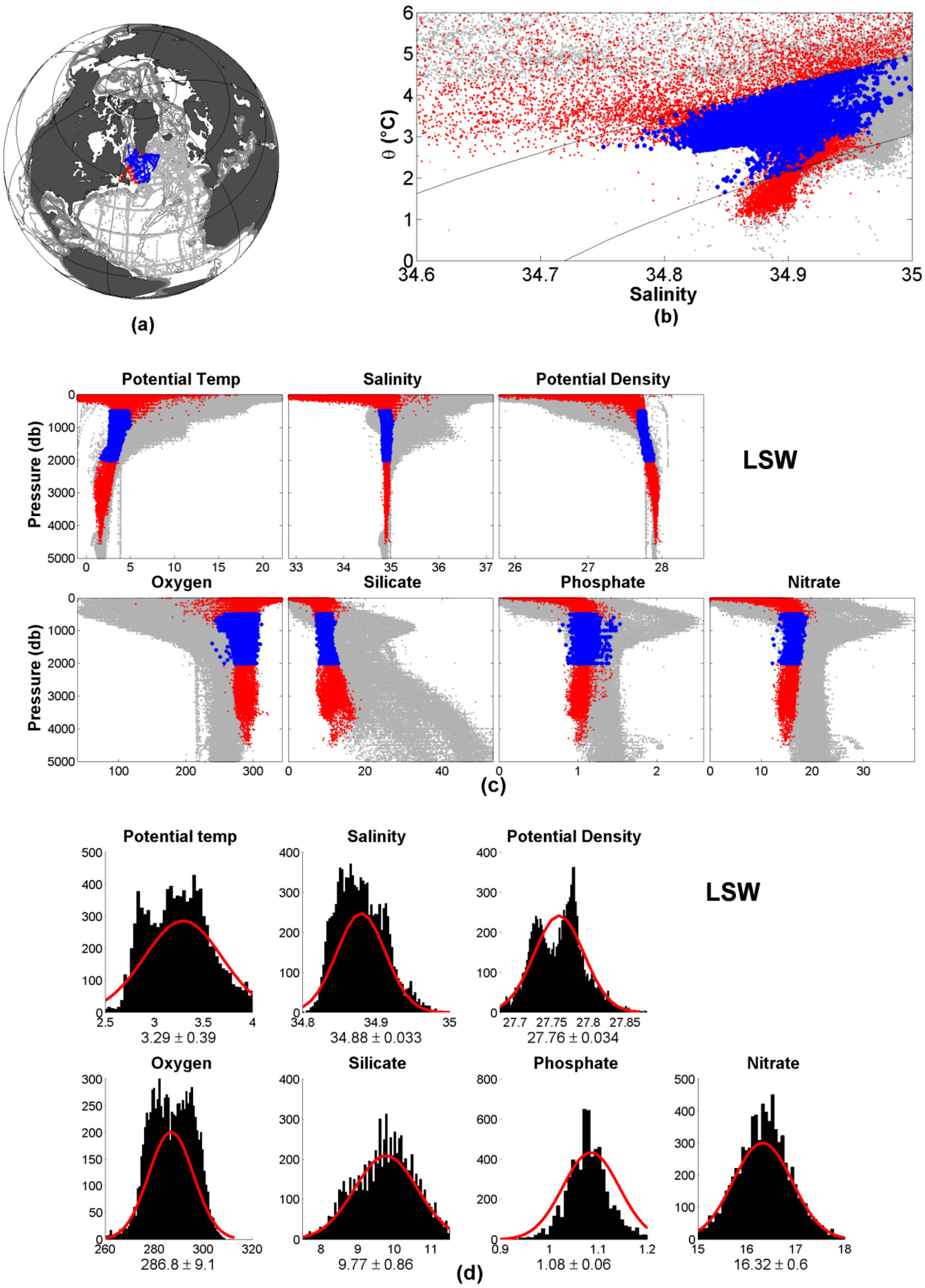

Figure 12: Overview of Labrador Sea Water (LSW):

Panel a) shows the formation area used to define the water mass, panel b) show a T-S diagram and panel c) the distribution of key properties vs. pressure. In panel d) we show bar plots of the data distribution of samples used to define the water mass. Potential Temperature in (°C), Potential Density in kg/m^3, Oxygen and nutrients in µmol/kg^3. The red Gaussian fit shows mean and σ based on selected data.

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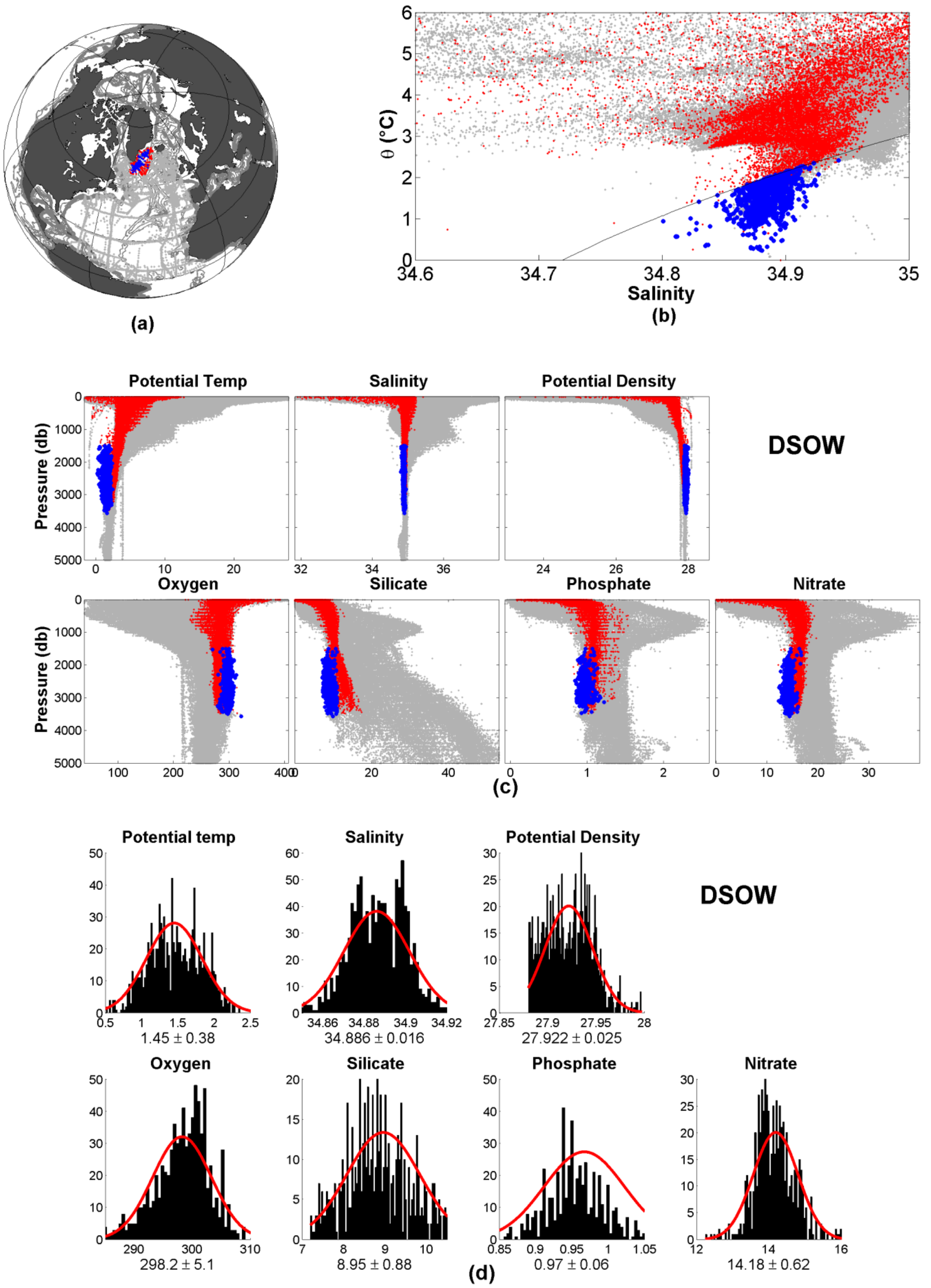

Figure 13: Overview of Denmark Strait Overflow Water (DSOW):

Panel a) shows the formation area used to define the water mass, panel b) show a T-S diagram and panel c) the distribution of key properties vs. pressure. In panel d) we show bar plots of the data distribution of samples used to define the water mass. Potential Temperature in (°C), Potential Density in kg/m^3, Oxygen and nutrients in µmol/kg^3. The red Gaussian fit shows mean and σ based on selected data.

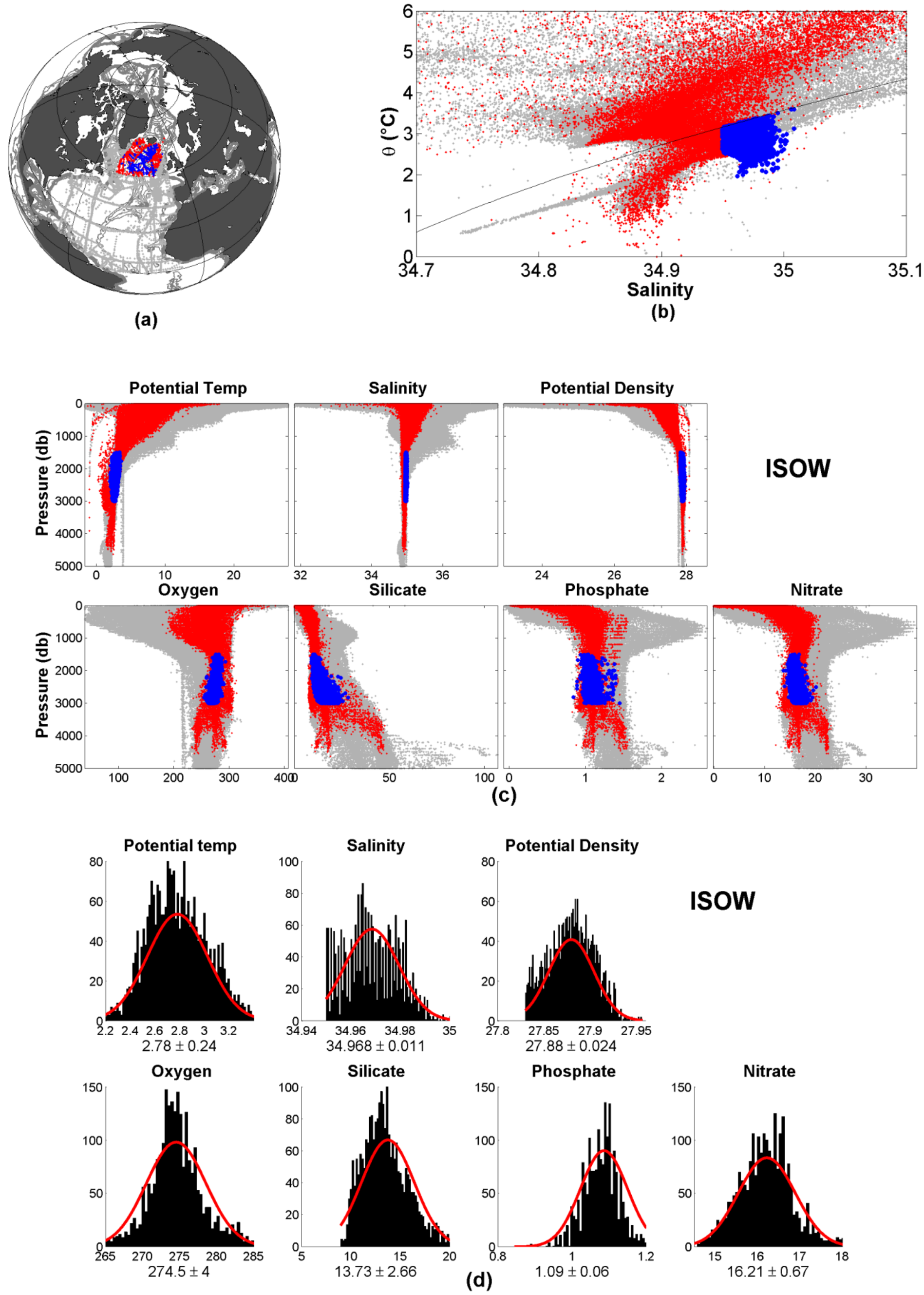

Figure 14: Overview of Iceland-Scotland Overflow Water (ISOW):

Panel a) shows the formation area used to define the water mass, panel b) show a T-S diagram and panel c) the distribution of key properties vs. pressure. In panel d) we show bar plots of the data distribution of samples used to define the water mass. Potential Temperature in (°C), Potential Density in kg/m^3, Oxygen and nutrients in µmol/kg^3. The red Gaussian fit shows mean and σ based on selected data.

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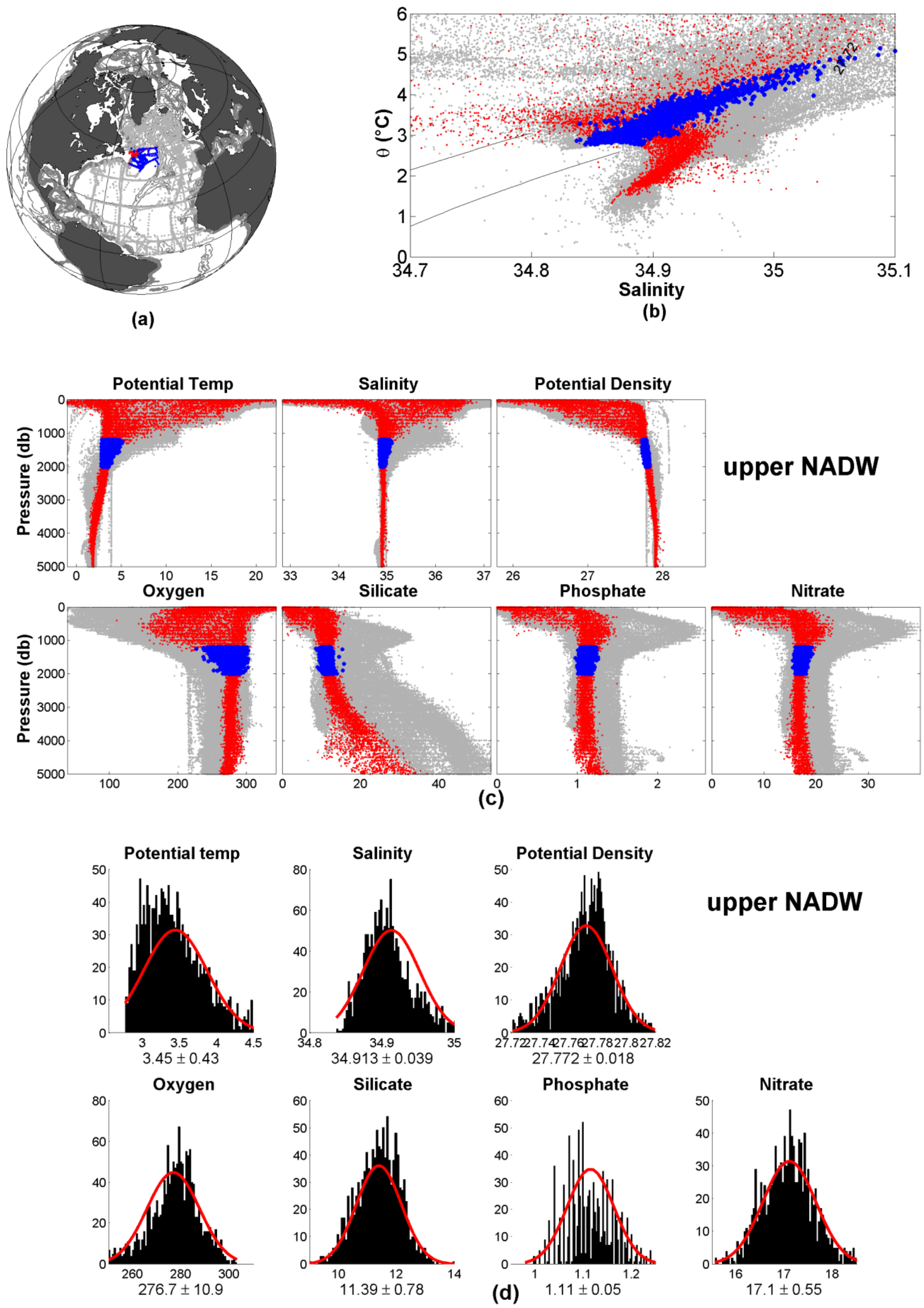

Figure 15: Overview of upper North Atlantic Deep Water (uNADW):

Panel a) shows the formation area used to define the water mass, panel b) show a T-S diagram and panel c) the distribution of key properties vs. pressure. In panel d) we show bar plots of the data distribution of samples used to define the water mass. Potential Temperature in (°C), Potential Density in kg/m^3, Oxygen and nutrients in µmol/kg^3. The red Gaussian fit shows mean and σ based on selected data.

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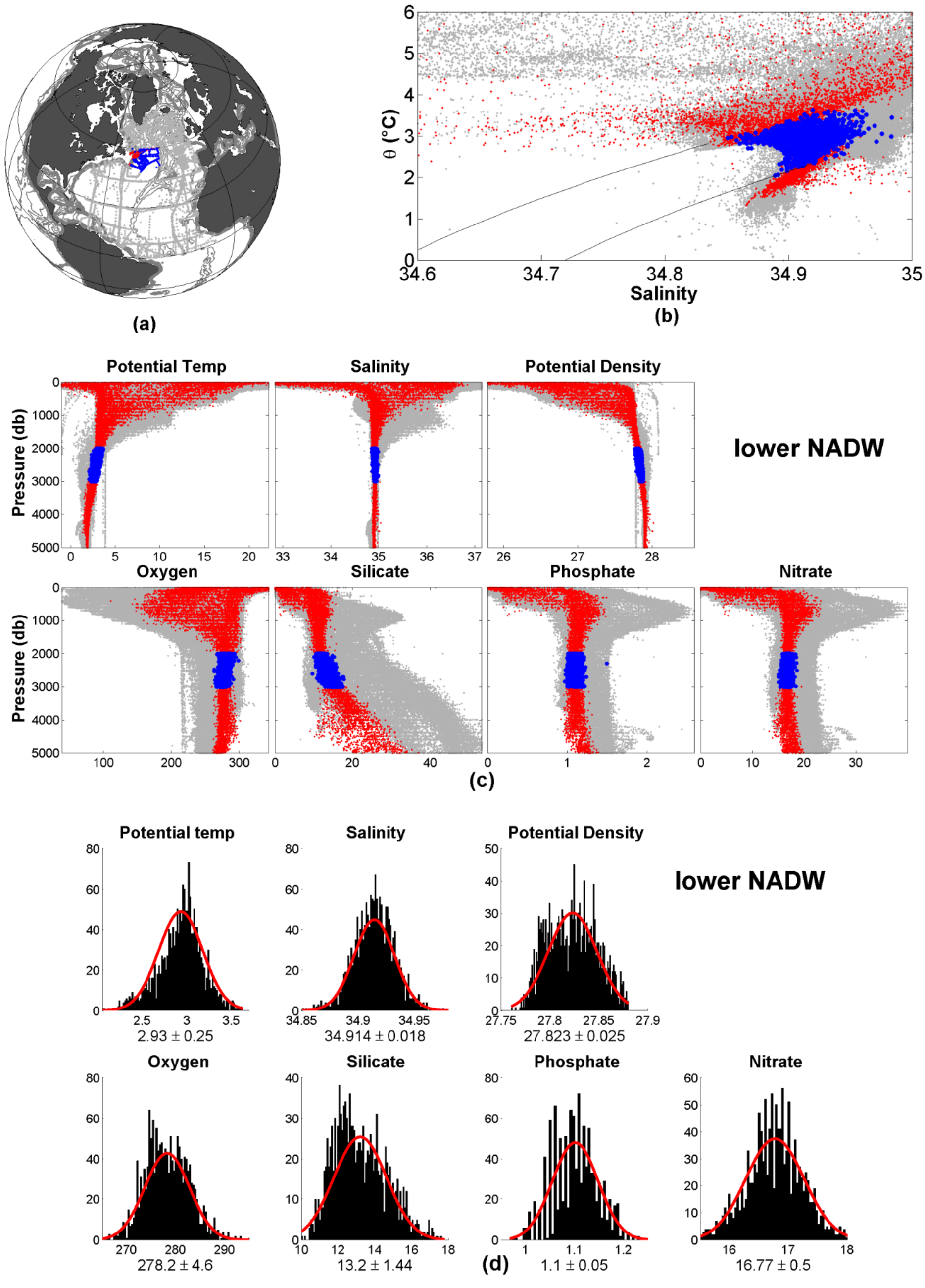

Figure 16: Overview of lower North Atlantic Deep Water (lNADW):

Panel a) shows the formation area used to define the water mass, panel b) show a T-S diagram and panel c) the distribution of key properties vs. pressure. In panel d) we show bar plots of the data distribution of samples used to define the water mass. Potential Temperature in (°C), Potential Density in kg/m^3, Oxygen and nutrients in µmol/kg^3. The red Gaussian fit shows mean and σ based on selected data.

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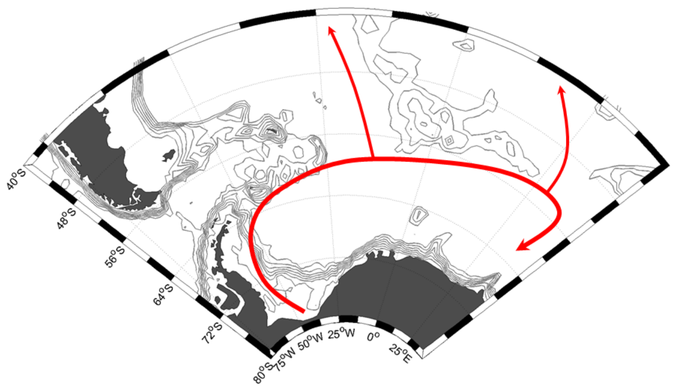

Figure 17: The water mass formation areas and the schematic of main currents in the Bottom Layer

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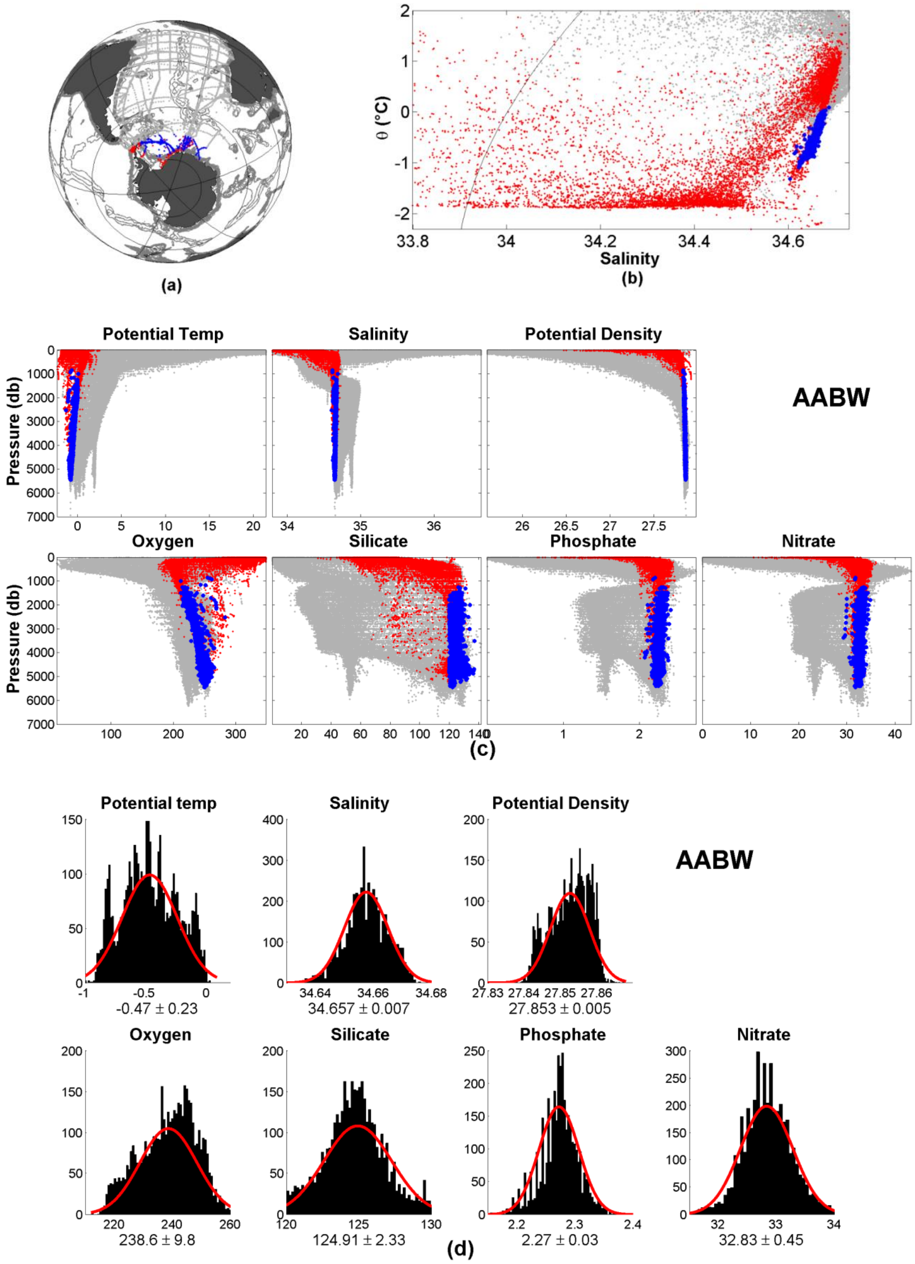

Figure 18: Overview of Antarctic Bottom Water (AABW):

Panel a) shows the formation area used to define the water mass, panel b) show a T-S diagram and panel c) the distribution of key properties vs. pressure. In panel d) we show bar plots of the data distribution of samples used to define the water mass. Potential Temperature in (°C), Potential Density in kg/m^3, Oxygen and nutrients in µmol/kg^3. The red Gaussian fit shows mean and σ based on selected data.

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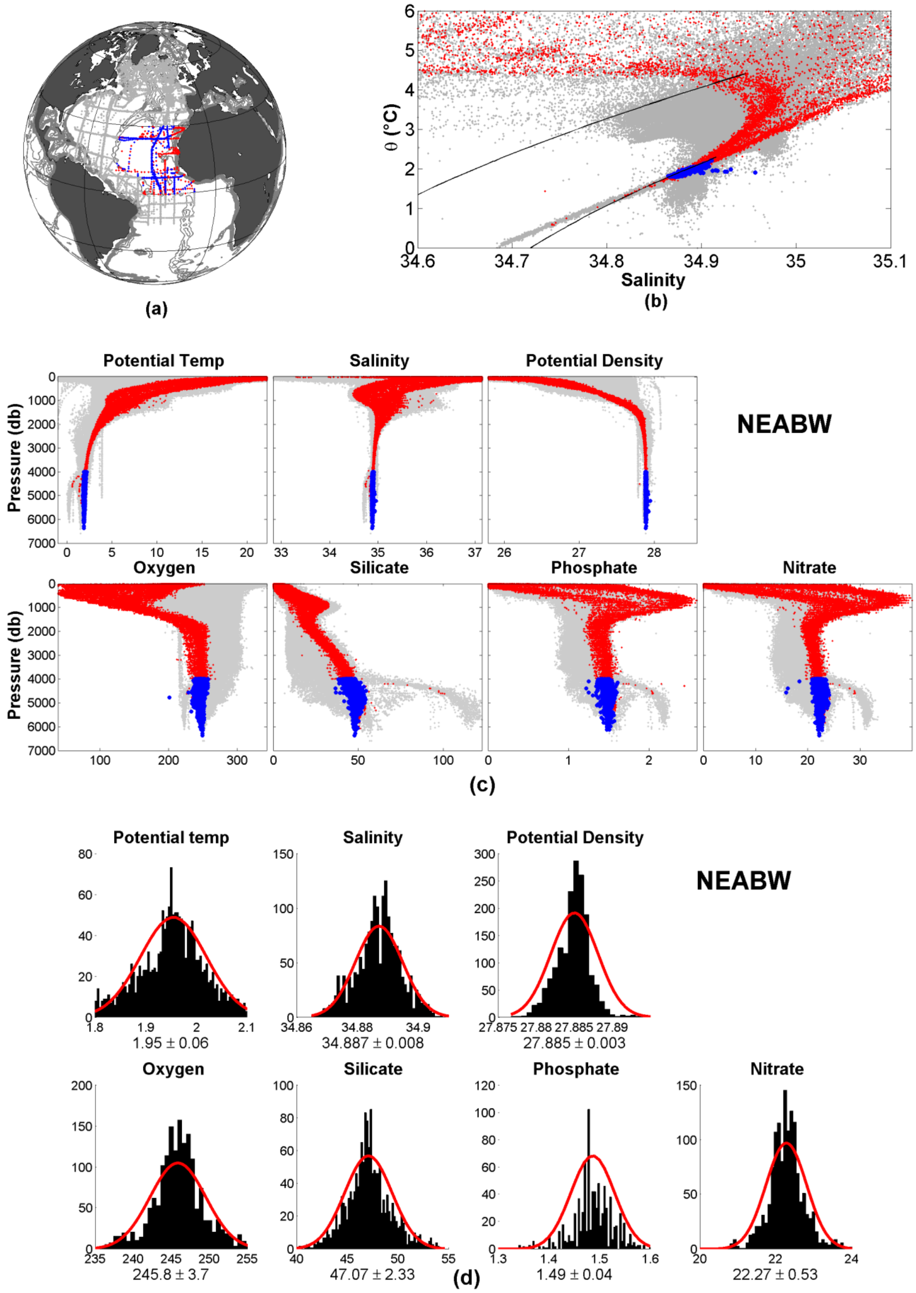

Figure 19: Overview of Northeast Atlantic Bottom Water (NEABW):

Panel a) shows the formation area used to define the water mass, panel b) show a T-S diagram and panel c) the distribution of key properties vs. pressure. In panel d) we show bar plots of the data distribution of samples used to define the water mass. Potential Temperature in (°C), Potential Density in kg/m^3, Oxygen and nutrients in µmol/kg^3. The red Gaussian fit shows mean and σ based on selected data.

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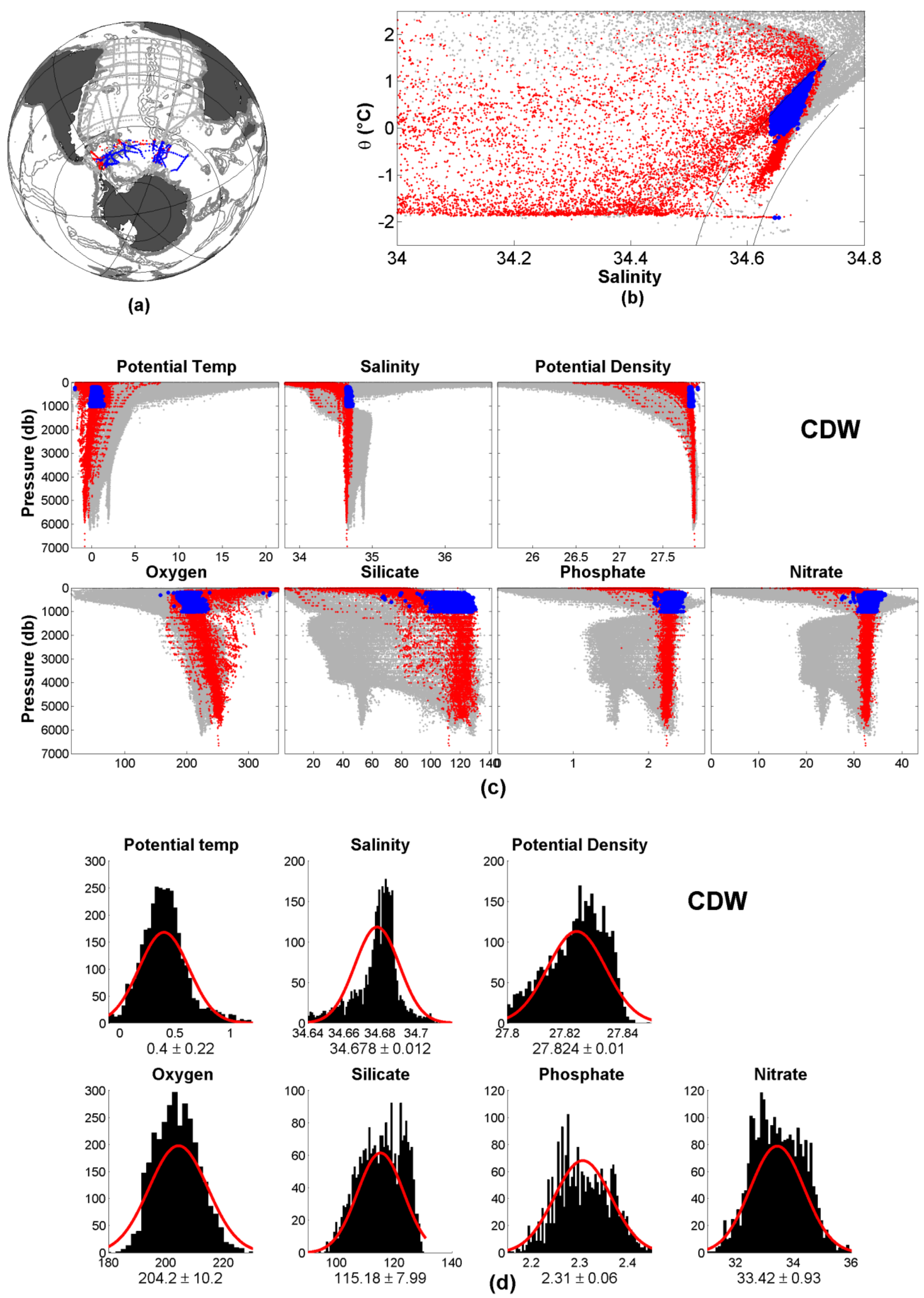

Figure 20: Overview of Circumpolar Deep Water (CDW):

Panel a) shows the formation area used to define the water mass, panel b) show a T-S diagram and panel c) the distribution of key properties vs. pressure. In panel d) we show bar plots of the data distribution of samples used to define the water mass. Potential Temperature in (°C), Potential Density in kg/m^3, Oxygen and nutrients in µmol/kg^3. The red Gaussian fit shows mean and σ based on selected data.

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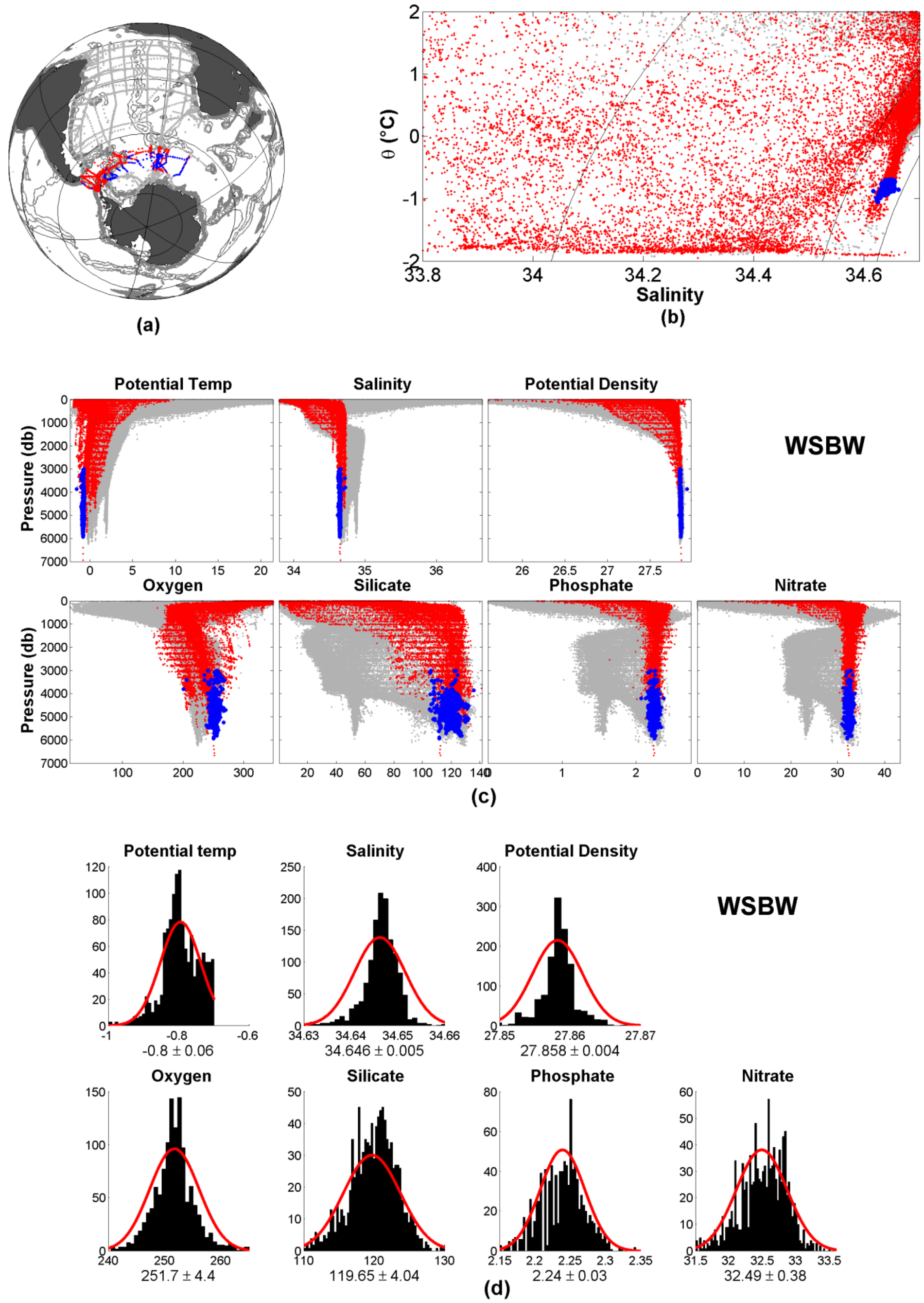

Figure 21: Overview of Weddell Sea Bottom Water (WSBW):

Panel a) shows the formation area used to define the water mass, panel b) show a T-S diagram and panel c) the distribution of key properties vs. pressure. In panel d) we show bar plots of the data distribution of samples used to define the water mass. Potential Temperature in (°C), Potential Density in kg/m^3, Oxygen and nutrients in µmol/kg^3. The red Gaussian fit shows mean and σ based on selected data.

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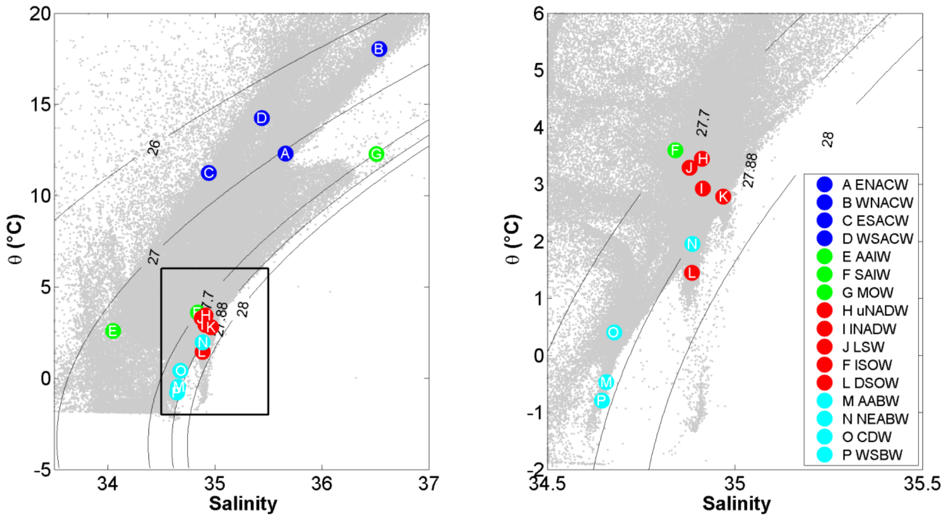

Figure 22: Potential temperature / Salinity distribution of the 16 main SWTs in the Atlantic Ocean discussed in this study. Colored dots with letters A-P show the mean value of each SWT and gray dots show all the data from GLODAPv2.

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Table 1: Table of all the water masses and the four main layers as defined in this study.

The variables defined are used to select water samples that defines water masses in the formation regions.

Layer	SWT	Longitude	Latitude	Pressure dbar	Potential Temperature °C	Salinity	Potential Density kg m^{-3}	Oxygen µmol kg^{-1}	Silicate µmol kg^{-1}
Upper Layer	ENACW	15°W—25°W	39°N—48°N	100 — 500	---	---	26.50—27.30	---	---
	WNACW	50°W—70°W	24°N—37°N	100 —1000	---	---	26.30—26.60	---	< 3
	WSACW	25°W—60°W	30°S—45°S	100 —1000	---	> 34.5	26.00—27.00	< 230	< 5
	ESACW	0—15°E	30°S—40°S	200 — 700	---	---	26.00—27.20	200--240	< 10
Intermediate Layer	AAIW	25°W—55°W	45°S—60°S	> 300	> -0.5	---	26.95—27.50	> 230	< 30
	SAIW	35°W—55°W	50°N—60°N	100 — 500	> 4.5	< 34.6	> 27.65	---	---
	MOW	6°W—24°W	33°N—48°N	> 300	---	36.35—36.65	---	---	---
Deep and Overflow Layer	uNADW	32°W—50°W	40°N—50°N	1200—2000	---	---	27.72—27.82	---	---
	lNADW	32°W—50°W	40°N—50°N	2000—3000	---	---	27.76—27.88	---	---
	LSW	24°W—60°W	48°N—66°N	500 —2000	---	---	27.68—27.88	---	---
	ISOW	0—45°W	50°N—66°N	1500—3000	---	> 34.95	> 27.83	---	---
	DSOW	19°W—46°W	55°N—66°N	>1500	---	---	> 27.88	---	< 11
Bottom Layer	AABW	---	> 63°S	---	---	---	>28.27	---	> 120
	CDW	< 60°W	55°S—65°S	200—1000	0—1	> 34.64	> 27.80	---	---
	WSBW	---	55°S—65°S	3000---6000	< -0.7	---	---	---	> 105
	NEABW	10°W—45°W	0—30°N	> 4000	> 1.8	---	---	---	---

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Table 2: The full name of the water masses discussed in this study, and the abbreviation.

Full name of Water Mass	Abbreviation
East North Atlantic Central Water	ENACW
West North Atlantic Central Water	WNACW
West South Atlantic Central Water	WSACW
East South Atlantic Central Water	ESACW
Antarctic Intermediate Water	AAIW
Subarctic Intermediate Water	SAIW
Mediterranean Overflow Water	MOW
Upper North Atlantic Deep Water	uNADW
Lower North Atlantic Deep Water	lNADW
Labrador Sea Water	LSW
Iceland-Scotland Overflow Water	ISOW
Denmark Strait Overflow Water	DSOW
Antarctic Bottom Water	AABW
Circumpolar Deep Water	CDW
Weddell See Bottom Water	WSBW
Northeast Atlantic Bottom Water	NEABW

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Table 3: Table of the mean value, and the standard deviation, of all variables for all the water masses discussed in this study.

Layer	SWTs	Potential Temperature (°C)	Salinity	Potential Density (kg m^{-3})	Oxygen (µmol kg^{-1})	Silicate (µmol kg^{-1})	Phosphate (µmol kg^{-1})	Nitrate (µmol kg^{-1})
Upper Layer	ENACW	12.31±0.95	35.662±0.124	27.039±0.097	234.4±13.2	3.67±1.20	0.57±0.16	9.34±2.38
	WNACW	18.03±0.47	36.536±0.079	26.441±0.069	204.3±9.3	1.32±0.46	0.17±0.06	3.68±1.16
	ESACW	11.26±2.25	34.944±0.272	26.659±0.207	219.2±9.1	5.50±1.96	0.96±0.31	13.27±4.73
	WSACW	14.27±2.02	35.439±0.320	26.451±0.191	216.0±6.2	2.60±0.99	0.56±0.24	6.85±3.60
Intermediate Layer	AAIW	2.58±0.56	34.051±0.135	27.148±0.125	303.2±28.1	15.68±6.78	1.79±0.23	24.65±2.95
	SAIW	3.60±0.41	34.841±0.043	27.700±0.025	294.9±8.9	8.57±0.74	1.04±0.06	15.69±0.86
	MOW	12.28±0.77	36.510±0.081	27.704±0.150	186.3±10.7	7.22±1.75	0.74±0.11	12.61±1.96
Deep and Overflow Layer	uNADW	3.45±0.43	34.913±0.039	27.772±0.018	276.7±10.9	11.39±0.78	1.11±0.05	17.10±0.55
	uNADW	2.93±0.25	34.914±0.018	27.823±0.025	278.2±4.6	13.21±1.44	1.10±0.05	16.77±0.50
	LSW	3.29±0.39	34.880±0.033	27.760±0.034	286.8±9.1	9.77±0.86	1.08±0.06	16.32±0.60
	ISOW	2.78±0.24	34.968±0.011	27.880±0.024	274.5±4.0	13.73±2.66	1.09±0.06	16.21±0.67
	DSOW	1.45±0.38	34.886±0.016	27.922±0.025	298.2±5.1	8.95±0.88	0.97±0.06	14.18±0.62
Bottom Layer	AABW	-0.47±0.23	34.657±0.007	27.853±0.005	238.6±9.8	124.91±2.33	2.27±0.03	32.83±0.45
	CDW	0.40±0.22	34.678±0.012	27.824±0.010	204.2±10.2	115.18±7.99	2.31±0.06	33.42±0.93
	WSBW	-0.80±0.06	34.646±0.005	27.858±0.004	251.7±4.4	119.65±4.04	2.24±0.03	32.49±0.38
	NEABW	1.95±0.06	34.887±0.008	27.885±0.003	245.8±3.7	47.07±2.33	1.49±0.04	22.27±0.53