Reply to the comments from Report 1 (Anonymous Referee #3)

Peer review report on “Characteristics of Water Masses in the Atlantic Ocean based on GLODAPv2 dataset” by Mian Liu and Toste Tanhua

1) Overview and general recommendation:

Understanding the formation, transformation, and circulation of water masses has been a hot topic in oceanography since its start. Many ways of tangling this oceanography field have been developed, from the mere description of hydrographic properties to statistical and numerical models. This manuscript presents the water mass structure of the Atlantic Ocean resulting from an Optimum Multiparameter (OMP) analysis.

Although the intention of the manuscript is honorable, trying to facilitate the interpretation of biogeochemical results, the findings of the manuscript do not add any new information to the community. I would consider reducing the extension of this work and merging it with the companion paper. In the case the work would have to stand from itself, a much deep discussion of the results would be needed. Besides, the reliability of the OMP results has not be proven, by, for example, analyzing the residuals.

The manuscript needs a very careful proofreading and the number of figures/subplots in the main text needs to be reduced.

2) General comments:

1. After previous reviewers highlighted the need of a careful proofread of the manuscript, the manuscript still presents grammatical errors and misspellings. To highlight some:

   We have carefully proofread the whole manuscript, hopefully with fresh eyes so that we caught any remaining errors.

   a. There are still two appearances of STW instead of SWT (lines 325 and 355).

      Two mistakes have been fixed and all "STW" in this manuscript are guaranteed to be replaced by SWT.

   b. The term "sea water type" still appears in the manuscript instead of "source water type" (line 160 and Table 4 caption).

      Two mistakes have been fixed and all "sea water types" in this manuscript are guaranteed to be replaced by "source water type".

   c. There are inconsistencies in units. For example, sometimes density units are written as kg m^{-3} and others as kg/m^3.

      All the unit formats have been unified as kg m^{-3} or μmol kg^{-1}

   d. Sloppy proofread can be seen, for example, on lines 181 (“…is that he water masses…”)

      Checked, “the water masses”.

      306 (“…our analysis. The region…”),
Checked, “our analysis”.

423-424 (“…being important to distinguishe AAIW from Central Waters…”),
Checked, “being important to distinguish AAIW”.

and 536 (“vintages” of LSW exitst), to enumerate some.
Checked, “vintages” of LSW exist”.

Besides, there are grammatical errors, such as those on lines 49 (“there are gradual transformation between them”, where “transformation” should be plural),
Checked, “gradual transformations between them” in plural form.

and 52-53 (“Also important is the concepts”, it should be either “important is the concept” or “important are the concepts”);
Checked, “Also important is the concept” in singular form.

and sentences that are unfinished, such as the one on line 126 (“…water masses, since this product is.”).
Checked and the sentence has been completed.

e. One citation is not correctly spelled in the text (line 68, should be Jacobsen (1927)).
Checked, Jacobsen (1927).

There are also few references not cited in the text, such as Clarke et al. (1990); Ishii et al. (2011); Key et al. (2010); Lacan and Jeandel (2004); to enumerate some.
The references are checked again.

2. To solve the OMP for the whole Atlantic Ocean, the authors split the water column into different regions and layers (as summarized in Table 1), called OMP runs. Some suggested improvements for the OMP analysis:

a. After changing the description of the Central Waters by using two SWTs, the two SWTs defining each Central Water are not allowed to mix between them between 40N and the Equator (#5 upper and lower), so the transition between the different properties of the Central Waters observed in the ocean cannot be represented by the OMP. Besides, in Table 1 there is no specification of which of the two SWTs (or if the two SWTs) representing each one Central Waters they use that when solving the OMP system, such as in #6 and #8, for example. Please specify to avoid confusion.

Additional text is added to explain the divisions of OMP runs, including in both horizontal and vertical directions and also the reasons.

b. Lines 205-206: If the SWTs allowed to mix in each of the OMP runs have a coherent lateral and vertical distribution not such “step-like” features should appear. Each run should share at least one SWT with the adjacent OMP runs to avoid that issue, which seems to be the case according to Table 1. However, drastic disappearances/appearances of water masses can be observed in the top panels of Figure 19, highlighting the lack of a “transitional water mass” between AABW and NEADW.
Thanks for the suggestion. The OMP calculations have been redone with new criteria and now the “step-like” features between each runs were removed, especially in the A16 section. In the bottom layer, distributions of AABW and NEABW are more coherent (top panels of Figure 19). In the case of AABW and NEABW the steps do occur since we, for reasons outlined in the paper, consider a northern version of AABW north of the equator. Normally we have water masses in several boxes to avoid this, but the OMP can only handle so many water masses in one run.

c. Lines 207-214: There is no figure supporting what is discussed there, and what is 100% is the mass conservation itself not the residual, the residual should be 10% or 20% (same for line 36-37). Besides, if all the required SWTs are defined and the weighting of the OMP equations is well performed, an error in the mass conservation of 20%, even 10% should not happen.

This part is discussed together with an additional section. Mass residual is inevitable in the central water, even in the paradigm of the OMP founders (see figure below). The reason is also explained in the data and method section. The key properties, for instance CT, of Central Waters are variable. When the CT increases beyond the range of this water mass, the OMP analysis considers the fraction is over 100%, even more than 120%. In the other case, the new OMP calculation has been limited this situation in our manuscript within a small number (~8% of the total samples) of samples and values no more than 105%.

d. There is no discussion about the residuals of the OMP analysis. The residuals of the least square method constrained to non-negative solutions used for an OMP analysis give insights about the reliability of the proposed mixing model, and indicate the quality of the solution.

This point is discussed in the same paragraph together with c.

e. Figure 6 shows high percentages of ENACW along the Gulf Stream. That highlights the fact that that water mass is formed in the intergyre region (Pollard et al., 1996) and not close to the Iberian Peninsula. Changing the formation region for ENACW would result in a wider temperature and salinity range for ENACW than the one considered in this work.
Thanks for this helpful suggestion. The formation area is changed to the west according to Pollard et al., 1996. (Figure 5a and Figure 7 left panel), and the property range and distribution of ENACW become wider.

f. Figures 7 (WSACW) and 14 (ISOW) show water masses outside the range they should appear. Fig. 7 shows WSACW below $\sigma_\theta = 27.00$ kg m$^{-3}$, which should not appear according to Table 1 (below that density, OMP run #8 should be applied, which does not include WSACW). In Fig. 14, ISOW seems to extend to surface with percentages around 10% (guessing from the color scale), where it is not allowed according to Table 1. These two facts question how the OMP runs were applied to the dataset.

The drawing process of Figure 7 and all the other section plots is divided into two steps. In the first step, OMP analysis is used to calculate the water mass fractions in each sampling point and then splicing together. (The figure below shows an example from A16 section.) In the second step, objmap function in MATLAB is used for interpolation calculation to draw the section plot. Therefore, the reason why WNACW appears below $\sigma_\theta = 27.00$ kg m$^{-3}$ (new boundary is $\gamma = 27.10$ kg m$^{-3}$) is not because of OMP analysis, but the result from the objmap in the interpolation calculations from all the sampling points.

![Fractions of AAIW in each sampling point along A16 Section](image)

Thanks to the reviewer for pointing out my negligence in my work. I think it is reasonable for about 10-20% of WNACW still to appear on the boundary of $\sigma_\theta = 27.00$ kg m$^{-3}$ (new boundary is $\gamma = 27.10$ kg m$^{-3}$), while it is definitely wrong for ISOW to appear on the surface at any fraction. But this is not the error of OMP analysis, but the vulnerability of the objmap interpolation calculation. Therefore, the calculation method of objmap was adjusted in the new calculation, and such mistake has been avoided.

g. Both reviewers highlighted the fact that some samples are not accounted by any water type, and no change has been made to solve this issue. This is clearly seen in Fig. 2 (previously Fig. 22).

One paragraph is added in the discussion section to explain this point.

3. There is a good explanation on how the regions of water mass formation where selected to determine the SWT properties, but the discussion of the OMP results, i.e., the water mass distributions comparing them against previous works is almost inexistent. If this works wants to stand by itself, it needs a better discussion of the results, presenting what novelties have
been found. Some of the information to discuss with is already in the sections describing the formation regions of the water masses.

The text is reorganized in the new manuscript by adding the results and comparisons to the previous investigations and references.

3) Minor comments:

4. Line 26 and elsewhere: Once the MOW has overflowed the Strait of Gibraltar and has mixed with Atlantic Waters, it is no longer MOW but Mediterranean Water (MW) (see, for example, Carracedo et al., 2016). As in this work the depicted area of formation of MOW west of the Strait of Gibraltar (Fig. 9), please change MOW to MW here and elsewhere.

Accepted, Mediterranean Overflow Water and MOW are changed into Mediterranean Water and MW.

5. Introduction: New information has been added to the introduction, but a careful reorganization and summarization needs to be done in this section. The information is presented in a chaotic order, being some information repeated.

The introduction section has been reorganized.

6. Lines 156-158: This sentence is confusing. Consider rephrasing something like: “Some WMs need more than one SWT to be defined (Tomczak, 1999), for example Central Waters present a linear temperature-salinity relationship that requires two SWTs for a complete description.”.

Thanks for the suggestion, the expressions has been changed.

7. There is still a misuse of the terminologies water mass vs. source water type. For example, on lines 162 and 164 it is used the term WM instead of SWT, as it is correctly used on line 176. For an OMP analysis what is defined are the properties of the SWTs and not of the WMs.

Accepted, the distinguish between SWTs and WMs is further clarified in the new version.

8. On lines 189-191 it is stated that the mixed layer was not considered, but on lines 192-194 it is stated that all the Atlantic data present in Glodapv2 was analyzed. That creates confusion, please merge both sentences.

Checked and improved.

9. Line 195: to a reader not familiar with OMP it is not that clear why solving the fractions of 6 SWTs is an excessive number. Please clarify that the number of SWT fractions must be lower than the number of properties defining the SWTs in order to solve an overdetermined system of equations.

Accepted, and an explanation is added after consulting Karstenson, the founder of the OMP method.

10. Lines 241-251: as already pointed out by van Heuven, only key figures should be maintained in the main manuscript and the rest should be placed in the supmat. As a guidance, I would leave one of the figures referred in these lines (Figs. 5, 8, 11, 12, 16 and 17) in the main text as an example and move the others to the supplementary material.

Accepted, and the figure plots are reorganized.

11. Line 318: Salinity should be specified as a dimensionless quantity (Unesco, 1986).
Absolute Salinity (g kg$^{-1}$) is now used in the new version.

12. Lines 726 and 730: should it be “6-dimensional” and “Six often measured” according to the number of properties defining each SWT?

Accepted and changed.

13. Both reviewers rightly point to the fact samples near 34.8 salinity and -1oC temperature are not represented by the SWTs used in this work. van Heuven and the authors themselves determine that those samples are located in the Norwegian Sea, therefore those samples should not be considered in this work that focusses in the Atlantic Ocean. Therefore, those data points and those of the mix layer that were not being solved by the OMP analysis performed in this work should be removed from Figs. 2, 5, 8, 11, 12, 16, and 17.

These points are now removed from the OMP analysis and additional explanation is added in the end of the discussion section.

14. Figures: Pressure units should be dbar not db.

Accepted and changed.

15. Figure 2: I would recommend adding all the SWTs to the plots, and not only the central points in case of the Central Waters. Adding the two extremes of the TS-relationship would help the reader to know which samples are “enveloped” by the defined SWTs.

Accepted and changed.

16. Figures representing along section properties (Fig. 1) and waters mass distributions (Figs. 7, 8, 10, 14, 15, 19 and 20) will benefit from map insets (as Fig. 3) to avoid the reader to go back and forth to Fig. 2 to know where the section is located. In case such map insets are not added, please state that the cruise tracks are represented in Fig. 2.

Accepted and added.

17. Please, consider changing the color scale of Figs. 1, 3, 6-10, 12-15 and 18-20 to a colorblind-friendly one, such as the ones in the cmocean package: https://github.com/kthyng/cmocean-odv.

The color scale is changed and we hope this time can be seen more clearly, especially the fractions of water masses, which is the main point of this study.

4) References


Checked and corrected.
Reply to the comments from Report 2 (Referee #4: Groeskamp, Sjoerd)

This paper is an attempt to provide a very thorough analyses of water masses in the Atlantic Ocean. The authors have clearly done a lot of work, both in analyses, figures and text. Their objective seems to be, to provide some sort of look-up table on Atlantic Water masses that can be used for both physical and biogeochemical community in order to understand the formation and spread of water masses. This in itself is certainly useful, and in that regard, I think this paper is worthy of publication. However, this paper is not ready for publication.

It is not a lack of effort that is the problem. The authors have done a substantial job. It is because it is too much and yet too little. Too much because 1) a lot of the text can be shortened and 2) in the sense that they try and cover a lot of water-masses and therefore have to cover a lot of literature. On the other hand, too little because 1) a lot of the method and the science is not well explained or clearly laid out, and 2) they don’t cover all the literature for all the WM because that is perhaps impossible.

So, to me, there are two issues: 1) science, 2) presentation and text. The first requires a lot of work, as explained below. Even to just make this work reproducible by others. The second, I’m not sure what is the best option, but currently I think it may be too long and maybe still incomplete. Overall, I think this paper can be reduced to at least 75% of its current length just by being more precise, concise and to the point. Because this paper is already long, this is important. Some comments are also provided below.

The science

It is unclear which salinity is used. I assume Practical Salinity. These days we do not use potential temperature and “salinity”. We use Conservative Temperature and Absolute Salinity. These can easily be obtained using the TEOS-10 gsw software. Please use these or provide clear arguments why you do not use those variables.

Thanks for the suggestion. In the new version, Conservative Temperature (CT) and Absolute Salinity (SA) are used instead of Potential Temperature and Practical Salinity.

Section 2.2 and 2.3. Line 136 to 174. What exactly is the message of all this text? Basically, I read; “it’s difficult to define water masses, but Tomczak did a good job and we use his method”. If so, I think this can be a lot shorter. This would free up some space to then properly explain the method.

Thanks for the suggestion, the text is now simplified.

You provide one equation (L175), with little explanation. It is not clear where and how source waters are defined and how the related G-matrix would look like and what kind of numbers go into that matrix. Then it is unclear which data go’s into d and it is also unclear which method is used to find a minimum for R. Is this a least-squares inversion? If so, have you looked at the sensitivity to choices in the input parameters, such as how water masses are defined, and how much variables are used? Is any weighting used for the solution? These are all unanswered question that are important for reproducibility of the results.

A detailed explanation is added in the manuscript.

L181-184 This paragraph is unclear. Please provide numbers. What are “short” transport times, and how “close” is close enough and how to these numbers influence your results.
A specific number or transport time is difficult to define, in the new manuscript a general range or scale, for instance an oceanic front or basin-wide scale, is given according to Karstensen and Tomczak, (1998).

Section 2.3 and beyond. Nitrate and phosphate seem to have a very similar distribution. Using them both may not add that much information. In line 181-191 you then say you use them to construct a conserved variable. So, are you then using 5 instead of 6 variables? If so, this should be made very clear in the manuscript.

Correct, in the analysis, 5 are used instead of 6, but was not reflected and explained in the previous manuscript. This was a mistake in the work. Run 5 and 7 are now more subdivided in Table 1 and explained in the text in the new manuscript.

Also, for the conclusion section you talk about 7-dimensional space. Is it still if you combined tracers into one? On top of that, what do you do with Oxygen, as that is also non-conservative and, in these lines, you mention this could be a problem.

Accepted, changed to 6.

Because the explanation of L185-L214 is not always clear and the manner by which numbers are obtained is not well explained, I don’t understand L207-214. In addition, the authors talk about something in A16 in L208-209, but do not refer to where we can see this.

One additional section is added to give a detailed explanation for the OMP analysis.

You define 4 vertical layers based on surface-referenced potential density. First of all, how is this calculated? Do you use the TEOS-10 software? Second, why surface referenced potential density. This is not accurate beyond 500 meters depth for WM analyses. Please use Neutral Density, which is perhaps the best we currently have.

Thanks for the suggestion, Neutral Density is now used instead of Potential Density.

L261-278 Is this about figure 5 and beyond. It is not clear what the message of this paragraph is and where it belongs. Either remove it or clarify what the purpose is.

The purpose of this paragraph is to clarify some information in Figure 6 and 7 and beyond, including the Expocode, Stations, Sections, and also the source of the information. But this doesn’t seem to help much with the topic of the study, and most of the information is available to the reader from the figure legends, so it might be a better choice to remove this paragraph.

The writing and presentation

The authors have provided many figures with a lot of information. A lot of work has been done to do this properly. Still some improvements can be made. Overall, I think that the text needs to be written more concise, precise and to the point and can reduce to 75% of its current length.

**Introduction:** The authors attempt to write a little bit of history on the subject. It seems incomplete and maybe not necessary to the extent done here. It is partly a matter of style, but partly also a matter of being precise, concise and to the point. So, I think the introduction can shrink at last 25% and still convey the same information. Perhaps consider reading Groeskamp et al 2019, it provides a history on WM analyses and WM transformation.

Thanks for the suggestion, the Introduction section are reorganized and the text has been shortened.

**Section 4,5,6,7**
Each WM is introduced with some literature background. That is great. However, because so many WMs are considered, this of course requires a lot of literature study. I think the current references are all pretty old and some new insights can be included, from more recent studies. I can give one example of a WM which I’m more familiar with. For AAIW. Consider these papers: Over all


Thanks for the helpful suggestion, and new criteria are redefined in the OMP analysis.

I’m sure such additional work could be done for most WMs considered here. Now I’m not sure how much of this work you need to do to provide a reasonable background. Eventually, I’ll leave it up to the authors to decide if the current version is good enough or needs more work on that.

Correct, there is further work to be done on the water masses. In the next step, authors intend to introduce transient tracers (CFCs and SF₆) based on this work. For now, the current work can support the next step and after that, the authors will try to investigate the water masses in a meticulous and deep-going way in order to support the demand of biogeochemistry research.

Line 115-134 can be merged into one brief paragraph half the size. Accepted, and the text is reorganized in the new version of manuscript.

L181 - What is internally consistent? I don’t think this is a useful description. The description is reorganized.

L241 – During the narrative of each water mass. What does that mean? Expression changed, during definition of SWTs.

L244 – which colour coding? Explained, all the selected data (blue dots) in Figure 6 and 7.

L256-260 – Good point, but not very clearly explained. Please try again. Accepted, and the explanation is reorganized in the new manuscript.

**Figure 2:** When Figure 2 is first mentioned in text, SWT is not yet defined. But it is used in the caption. That should be clarified. It is unclear where the colours stand for. Please provide link to abbreviations in caption, they have not been discussed yet. Please provide in caption, the clarification that the middle panel is a zoom of the box in the left panel. The letters in the light blue can’t be read.

Correct, the order of the figures has been rearranged and more clear instructions have been added, in addition, the details of the figures have been changed.
A few examples of incomplete, misspelled, or weird sentences. This needs work:

- L181 that the
- L194 .
- L211 weird sentence
- Where is section 8?

Checked and corrected.
Characteristics of Water Masses in the Atlantic Ocean based on
GLODAPv2 dataset: Characteristics and Distributions

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Abstract: The characteristics of a large number of the main water masses are presented in the Atlantic Ocean are investigated and defined. Knowledge of their distributions and properties are important for understanding and monitoring of a range of oceanographic phenomena. The characteristics and distributions of water masses in biogeochemical space are useful for, in particular, chemical and biological oceanography to understand the origin and mixing history of water samples. Here we define the characteristics of the major water masses in the Atlantic Ocean as Source Water Types (SWTs) from their formation areas, and map out their distributions. The SWTs are described by six key properties based on the GLODAP observational data. These include both conservative (potential temperature and absolute salinity) and non-conservative (oxygen, silicate, phosphate and nitrate) variables. The distributions of these water masses are investigated with the use of the Optimal Multi-Parameter (OMP) method and mapped out. The Atlantic Ocean is divided into four vertical layers by distinct potential-neutral densities in the shallow and intermediate water column, and additionally by concentration of silicate in the deep water and four zonal layers to guide the identification and characterization. The water masses in the upper layer originate from winter-time 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). Waters. Below the upper layer, the intermediate layer consists of three main water masses: Antarctic Intermediate Water (AAIW), Subarctic Intermediate Water (SAIW) and Mediterranean Overflow Water (MOWMW). The North Atlantic Deep Water (NADW, divided into its upper and lower components) is the dominating water mass 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 the Denmark Strait Overflow Water (DSOW). The Antarctic Bottom Water (AABW) is the only natural water mass in the bottom layer and this water mass is redefined as North East Atlantic Bottom Water (NEABW) in the north of equator due to the change of key properties, especially silicate. Similar with NADW, two additional water masses, Circumpolar Deep Water (CDW) and Weddell Sea Bottom Water (WSBW), are defined in the Weddell Sea region in order to understand the origin of AABW. The distributions of the main water masses are further investigated with the use of the Optimal Multi-Parameter (OMP) method and mapped out with their core potential densities in the Atlantic Ocean. The mass conservation residual is inevitably larger than 100%, especially in the Central Waters, but it doesn't actually affect the determination to the distributions of water masses. The definitions of SWTs and distributions of water masses in biogeochemical space are useful for, in particular, chemical and biological oceanography to understand the origin and mixing history of water samples.

Key Words: Atlantic Ocean, Water Mass, Source Water Types, GLODAP, Optimal-Multi-Parameter Analysis
Introduction

Properties of the water in the ocean are not uniformly distributed so that different regions and depths (or densities) have different characteristics. Bodies of water with similar properties often share a common formation history and are referred to as a water mass. The ocean is composed a large number of water masses that are not simply piled up on top of, or next to each other, like bricks. In fact, water masses have no clear boundaries, instead there are gradual transformations between them (e.g., Castro et al., 1998). Understanding of the distributions and variations of water masses is important for properties of the water in the ocean not uniformly distributed and the characteristics varies with regions and depths (or densities). The water masses, which are defined as bodies of water with similar properties and common formation history, are referred to as a body of water with a measurable extent both in the vertical and horizontal, and thus a quantifiable volume (e.g., Helland-Hansen, 1916; Montgomery, 1958). Mixing occurs inevitably between water masses, both along and across density surfaces, and result in mixtures with different properties away from their formation areas. Understanding of the distributions and variations of water masses have significance to several disciplines of oceanography, for instance while investigating the thermohaline circulation of the world ocean or predicting climate change (e.g., Haine & Hall, 2002, Tomczak, 1999). Also important is the concepts (e.g., Haine and Hall, 2002; Tomczak and Godfrey, 2013; Morrison et al., 2015).

The concept of water masses is also important for biogeochemical and biological applications, where the transformations of properties over time can be successfully viewed in the water masses 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, García-Ibáñez et al. (2015), (Tanhua et al., 2005), Numbers of investigations show the significance of knowledge about water masses to the biogeochemical oceanography, for instance, the investigation of mineralization of biogenic materials (Alvarez et al., 2014) or the change of ventilation in the Oxygen Minimum Zone (Karstensen et al., 2008). In a more recent work, García-Ibáñez 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. However, the lack of a unified definition of overview water masses on an oceanic or even global scale leads to an additional and repetitive amount of work by redefining water masses in specific regions. The goal of this study is to facilitate water mass analysis in the Atlantic Ocean and in particularly we aim at supporting biogeochemical and biological oceanographic work in a broad sense.

A water mass is a body of water that originates in a particular area of the ocean with a common formation history, in other words, seawater from one water mass shares common properties such as temperature, salinity, and biogeochemical properties that are distinct from surrounding bodies of water (e.g., Montgomery, 1958, Helland-Hansen, 1916) and have a measurable extent both in the vertical and
horizontal, and thus a quantifiable volume. Since each water mass is surrounded by other water masses, mixing occurs inevitably between them both along and across density surfaces. As a result, mixtures of water masses with different properties tend to be found away from their formation areas. Early work by Jacobson (1927) and Defant (1929) clarified the application of T-S relationship in the oceanography, and 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. Since the first publication of global distributions of water masses (Sverdrup, 1942), early studies on water masses are mainly based on potential temperature (θ) and salinity (S). Emery and Meincke (1986) made a summary and review on this kind of analysis. The limitation of this method is that distribution of more (more than three) water masses cannot be calculated at the same time with only these two parameters. So during the same time as the development of this theory, physical and chemical oceanographers also tried to add more parameters to the calculation and the Optimum Multi-parameter (OMP) analysis is one of the typical products (Poole & Tomczak, 1999). This concept of water masses has been redefined over time, and in Emery and Meincke (1986) the water masses were divided into upper, intermediate and deep/abyssal layers based on the depth and the T-S relationship. With the development of observational capacities for a range of variables and the data base to evaluate them, definition of water masses is not limited to the T-S-P relationship. Additional physical and chemical properties, both conservative and non-conservative, are added to the water mass concept (e.g. Tomczak, 1981). These additional variables exhibit different importance in defining different water masses, but are complementary to each other and provide a more solid basis for water mass definitions. Based on research during last several decades, Tomczak (1999) summarized the history of the water mass research and provided an outlook for the evolution of water mass research. Tomczak (1981) extended the analysis into more than three water masses by adding more parameters/water properties (such as phosphate and silicate) and solving the equations of linear mixing without assumptions. In Tomczak and Large (1989), this method was successfully applied to the analysis of mixing in the thermocline in Eastern Indian Ocean. Accurate definition and characterization of water masses is the first step for performing any further analysis, such as the Optimum Multi-parameter (OMP) analysis (Tomczak & Large, 1989). In this study, the concepts and definitions of water masses as given by Tomczak (1999) are used and we aim at defining the properties of the main water masses in the Atlantic Ocean, and to view the distribution of the water masses. In order to facilitate the water mass analysis, the Atlantic data from the data product GLODAPv2 (Lauvset et al., 2016) are used to identify and define the properties of the most prominent water masses in the Atlantic Ocean based on 6 commonly measured physical and biogeochemical variables (Figure 1). The goal of this work is to facilitate water mass analysis and in particular we aim at supporting biogeochemical and biological oceanographic work in a broad sense. The water masses in this study are defined in a static sense, i.e. they are assumed to be steady and do not change with time, and that our analysis is relatively coarse in that we do not consider subtle differences between closely related water masses 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. The definitions of water masses are further used to estimate the distributions of the water
masses representative sections/cruises in the Atlantic Ocean based on the GLODAPv2 dataset.

In Figure 2, an overview of the water masses considered in this study is shown in a Salinity-Temperature
plot where the water masses from the different layers are plotted in different colors. It is obvious that a
series of additional variables other than temperature and salinity is helpful, if not necessary, to reliably
distinguish different water masses from each other, and to calculate the fractions of water masses in a
water sample with a particular characteristic.

Understanding the formation, transformation, and circulation of water masses has been a research topic
in oceanography since the 1920s (e.g. Jacobsen, 1927; Defant, 1929; Wüst and Defant, 1936; Sverdrup,
1942 etc.). The early studies were mainly based on (potential) temperature and (practical) salinity as
summarized by Emery and Meincke (1986). The limitation of the analysis based on T—S relationship
is obvious; distributions of more (than three) water masses cannot be analyzed at the same time with
only these two parameters, so physical and chemical oceanographers has worked to add more parameters
to the characterization of water masses (e.g. Tomczak and Large, 1989; Tomczak, 1981; 1999). The
Optimum Multi-parameter (OMP) method extends the analysis so that more water masses can be
considered by adding parameters/water properties (such as phosphate and silicate) and solving the
equations of linear mixing without assumptions. The OMP analysis has been successfully applied in a
range of studies, for instance for the analysis of mixing in the thermocline in Eastern Indian Ocean
(Poole and Tomczak, 1999).

An accurate definition and characterization is the prerequisite for the analysis of water masses. In this
study, the concepts and definitions of water masses given by Tomczak (1999) are used and we seek to
define the key properties of main water masses in the Atlantic Ocean and further to view their
distributions. In order to facilitate the analysis, the data product GLODAPv2 is used to identify and
define the characteristics of the most prominent water masses based on 6 commonly measured physical
and biogeochemical properties (Figure 1). The water masses are defined in a static sense, i.e. they are
assumed to be steady and do not change with time and subtle differences between closely related water
masses are not considered in this basin-scale focus study. The definitions of water masses are in a
subsequent step used to estimate their distributions in the Atlantic Ocean, again based on the
GLODAPv2 data product. Detailed investigations on temporal variability of water masses, or their
detailed formation processes, for instance, may find this study useful but will certainly want to use a
more granular approach to water mass analysis in their particular areas.

2 Data and Methods

2.1 The GLODAPv2 data product
Marine Oceanographic surveys conducted by different countries have been actively organized and coordinated since late 1950s. WOCE (the World Ocean Circulation Experiment), JGOFS (Joint Global Ocean Flux Study) and OACES (Ocean Atmosphere Carbon Exchange Study) are the three typical representatives of international coordination in the 1990s. The GLODAP (Global Ocean Data Analysis Project) dataset was devised and implemented in this context with the aim to create a global dataset suitable to describe the distribution and interior ocean inorganic carbon variables (Key et al., 2004). Key et al., 2004; 2010). The first edition (GLODAPv1.1) contains data up to 1999 whereas the updated and expanded versions GLODAPv2 (Key et al., 2015; Olsen et al., 2016 and Key et al., 2015) was published in 2016 and the GLODAP team is now striving for annual updates (Olsen et al., 2019a; 2020). Since GLODAPv2 is a comprehensive and, more importantly, unbiased adjusted data product that includes relatively complete data and an almost global coverage.

In this work we use the GLODAPv2 data product (Olsen et al., 2016) to quantify the characteristics of water masses, since this product is. The data in the GLODAPv2 product has passed both a primary quality control (QC), aiming at precision of the data and unify the units, and a secondary data quality control, aiming at the accuracy of the data (Olsen et al., 2016; 2019). The GLODAPv2 data product is thus adjusted to correct for any biases in data. 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 (Tanhua et al., 2010). The GLODAPv2 data product is adjusted to correct for any biases in data through these QC routines and is unique in its internal consistency, and is thus an ideal product to use for this work aiming. 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 water masses.

The variables of absolute salinity (SA in g kg\(^{-1}\)), conservative temperature (CT in °C) and neutral density (\(\gamma\) in kg m\(^{-3}\)), which consider the thermodynamic properties such as entropy, enthalpy and chemical potential (Jackett et al., 2006; Groeskamp et al., 2016), are used in this study because they systematically reflects the spatial variation of seawater composition in the ocean, as well as the impact from dissolved neutral species on the density and provides a more conservative, actual and accurate description of seawater properties (Millero et al., 2008; Pawlowicz et al., 2011; Nycander et al., 2015).

### 2.2 Water Masses (WMs) and Source Water Types (SWTs)

In practice, defining properties of water masses (WMs) is often a difficult and time-consuming part, particularly when analyzing data from water masses in a region distant from their formation areas. An excellent discussion of water masses is found in Tomczak (1999), and we refer to this work for a more in depth discussion. Tomczak (1999) defines a water mass as "a body of water with a common formation history, having its origin and origins in a particular region of the ocean". Tomczak (1999) continues: "Water masses are physical entities with a measurable volume and therefore occupy a finite
volume in the ocean. In their formation region they have exclusive occupation of a particular part of the ocean; elsewhere they share the ocean with other water masses with which they mix. The total volume of a water mass is given by the sum of all its elements regardless of their location.”

Tomczak (1999) also introduces the concept of Source Water Types (SWTs). The SWTs describe the original properties of water masses in their formation areas, and can thus be considered as the original characteristics of water masses, and are also indispensable in labeling distributions of water masses (Tomczak, 1999). One difference is the distinction between the water masses and SWT concepts. While water masses define a physical extent, i.e. a volume, while SWTs are only mathematical definitions, i.e. SWTs are defined values of properties, or values without physical extents. In other words, water masses, as an objective existence in the ocean, have their temporal and spatial distributions, while SWTs, as an artificial definition, are only a concept of values. Knowledge of the SWTs, on the other hand, is essential in labeling water masses, tracking their spreading or mixing progresses, since the values from SWTs describe the initial characteristics of water masses. Or rather, the SWTs can and can be considered as the fingerprints of water masses and all the water masses can still be identified by their own SWTs, even when they spread distance away from their formation areas. The SWT of a water mass can be defined by several numbers and each number shows one key property. The SWT of a water mass is defined by the values of key properties, while some of them, like Central Water, cover a range between two numbers, by quantifying the concentration (Tomczak, 1999). Waters, require more than one SWT to be defined (Tomczak, 1999). In this study we will use the terminology “water mass” is used in the discussions, realizing that the properties of the water masses used for the water mass further analysis actually refer to sea water types—SWTs.

2.3 OMP Analysis

2.3.1 Principle of OMP Analysis

For the analysis in this study, six key properties are used to define water masses. These include SWTs, including two conservative properties (potential temperature and absolute salinity) and four non-conservative (oxygen, silicate, phosphate and nitrate) properties to define the water masses. In order to determine the distribution of water masses, distributions of water masses, the OMP analysis is invoked as an objective mathematical formulations of the influence of mixing is used. As a summary, Karsten and practical use of Tomczak, 1997, 1998). The starting point is the above results, the OMP analysis was developed and successfully applied in the analysis of water masses in specific regions (e.g. Karsten and Tomczak, 1998, Karsten and Tomczak, 1997). Observed properties are key properties (Figure 1) from a water sample are compared with observational sampling (such as CT, is the observational conservative temperature). The OMP model determines the contributions from predefined SWTs (such as CT, shows the properties of conservative temperature in each pure water masses to quantify SWT), which represent the mix of water masses that constitutes a water sample. The theory and formulas of the OMP analysis are described in detail in Tomczak and Large (1989).
and the website http://omp.geomar.de/. Here we make a brief introduction to the OMP calculation that relates directly to our research. OMP analysis is based on a simple model of "unmixed" WM in formation areas, through a linear set of following mixing equations, assuming that all key properties of water masses are affected by the same mixing process, and then to determine the distribution and of water masses through the following linear equation processes. The fractions (x_i) in each sampling point are obtained by finding the best linear mixing combination in parameter space defined by 6 key properties and minimizing the residuals (R, such as R\_CT is the residual of conservative temperature) in a nonnegative least squares sense (Lawson and Hanson, 1974) as shown in the following equations:

\[
\begin{align*}
G \cdot x_1 \cdot CT_1 + x_2 \cdot CT_2 + \cdots + x_n \cdot CT_n &= CT_{\text{obs}} + R_{CT} \\
x_1 \cdot SA_1 + x_2 \cdot SA_2 + \cdots + x_n \cdot SA_n &= SA_{\text{obs}} + R_{SA} \\
x_1 \cdot O_1 + x_2 \cdot O_2 + \cdots + x_n \cdot O_n &= O_{\text{obs}} + R_{O} \\
x_1 \cdot Si_1 + x_2 \cdot Si_2 + \cdots + x_n \cdot Si_n &= Si_{\text{obs}} + R_{Si} \\
x_1 \cdot Ph_1 + x_2 \cdot Ph_2 + \cdots + x_n \cdot Ph_n &= Ph_{\text{obs}} + R_{Ph} \\
x_1 \cdot N_1 + x_2 \cdot N_2 + \cdots + x_n \cdot N_n &= N_{\text{obs}} + R_{N} \\
\sum_{i=1}^{n} x_i &= 1 + R
\end{align*}
\]

Where the CT\_obs, SA\_obs, O\_obs, Si\_obs, Ph\_obs and N\_obs are the observed values of properties, the CT_i, SA_i, O_i, Si_i, Ph_i and N_i (i = 1, 2, ..., n) represent the predetermined (known) values in each SWT for each property.

The last row expresses the condition of mass conservation.

From the mathematics, the OMP analysis is an inversion of an overdetermined system in each sampling point, so that the sampling points are required to be located "downstream" from the formation areas, i.e. on the spreading pathway of the transport. The total number of WM which can be analyzed simultaneously within one OMP run is limited by the number of variables/key properties, because mathematically, 6 variables (x_1 - x_6) can be solved with 6 equations, i.e. In our analysis, one OMP run can burden up to 6 WM and the total number of WM (n) should not be larger than 6. The above system of equations can be written in matrix notation as:

\[
G \cdot x - d = R ;
\]

Where G is a parameter matrix of defined source water types(SWTs with 6 key properties in this study.), x is a vector containing the relative contributions of "unmixed" water type masses to the sample (i.e. solution vector of the source water type SWT_i fractions), d is a data vector of water samples (observational data from GLODAPv2 in this study) and R is a vector of residual. The solution is to find out the minimum the residual (R) with linear fit of parameters (key properties) for each data point with
a non-negative values. In this study, the mixed layer is not considered as its properties tend to be strongly variable on seasonal time-scales so that water mass analysis is inapplicable.

Prerequisites

2.3.2 Extended OMP Analysis

The prerequisite (or restriction) for using (basic) OMP analysis is that the water masses are defined closely enough to the observational water samples with short transport times within a limited ocean region, for instance an oceanic front or intertidal belt, so that the mixing can be assumed not influenced by biogeochemical processes (i.e. consider all the parameters as quasi-conservative).

However, the biogeochemical process cannot be ignored in a basin-scale analysis (Karstensen and Tomczak, 1998). Obviously, this prerequisite does not apply to our investigation for the entire Atlantic scale, so we use the "extended" OMP analysis is required. In this concept, non-conservative parameters (phosphate and nitrate) are converted into conservative parameters by introducing the "preformed" nutrients PO and NO, where PO and NO show the concentrations of phosphate and nitrate in seawater by considering the consumption of dissolved oxygen from respiration (in other words, the alteration due to respiration is eliminated) (Karstensen & Tomczak, 1998, Broecker, 1974). In this study, the mixed layer is not considered as its properties tend to be strongly variable on seasonal time-scales so that water mass analysis is inapplicable (Broecker, 1974; Karstensen and Tomczak, 1998). In addition, a new column should be added to the equations for non-conservative properties (aΔO2, aΔSi, aΔPh and aΔN) to express the changes in SWTs due to biogeochemical impacts, namely, the change of oxygen concentration with the remineralization of nutrients.

In order to map all the distribution of water masses in the Atlantic, all the GLODAPv2 data in the Atlantic Ocean are analyzed with the OMP method by using 6 key properties from each water sample (potential temperature, salinity, oxygen, silicate, phosphate and nitrate). Considering all the 16 main water masses in the Atlantic Ocean and to avoid excessive (more than 6) water masses in each OMP run, the Atlantic Ocean is artificially divided into different (total 13) OMP runs to remove water masses that are not likely to appear in the area. In the vertical, the 4-layer segmentation is based on potential density as well as silicate in the deep water. In the horizontal direction, the division lines are 40°N, the equator and 50°S. The area south of 50°S is treated as one area independent of density. Run 5 and run 7 are further divided into upper and lower boxes, due to the Central Waters, which cover two SWTs/boundaries in one OMP run. In this way, we end up with a set of 13 different OMP formulations that are used for estimating the fraction of water masses in each water sample. The density and the latitude of the water sample are thus used to determine which OMP should be applied (see Table 1CT1 + x2CT2 + …… + xCTn = CTobs + RCT

x1SA1 + x2SA2 + …… + xSAp = SAobs + RSA

x1O1 + x2O2 + …… + xO2 = Oobs + RO

x1Si1 + x2Si2 + …… + xSi3 + aΔSi = Siobs + RSi

\[ \sum x_i \Delta C = \Delta C_{obs} + R_{\Delta C} \]
\[ x_1 \text{Ph}_1 + x_2 \text{Ph}_2 + \cdots + x_n \text{Ph}_n + a \Delta \text{Ph} = \text{Ph}_{\text{obs}} + R_{\Delta} \]

\[ x_1 \text{N}_1 + x_2 \text{N}_2 + \cdots + x_n \text{N}_n + a \Delta \text{N} = \text{N}_{\text{obs}} + R_{\Delta} \]

\[ x_1 + x_2 + \cdots + x_n = 1 + R \]

As a result, the number of water masses should be further reduced in one OMP run if the biogeochemical processes are considered and extended OMP analysis is used. In this study, a total number of 5 water masses are included in each run.

2.3.3 Presence of mass residual

The fractions of WM s in each sample are obtained by finding the best linear mixing combination in parameter space defined by 6 key properties which minimizes the residuals (R) in a non-negative least squares sense. Note that all water masses are present in more than one OMP so that reasonable (i.e. realistic) transitions between the different areas can be realized. However, it is unavoidable that there will occasionally be step-like features across the vertical and horizontal boundaries defined in Table 1.

Ideally, a value of 100\% is expected when the fractions of all the water masses are added together, but in fact, the mass residual, which means a total value of more than 100\% are found for several samples. i.e. the mass conservation residual is larger than 100\%. For instance along the A16 Section\%, is inevitable during the analysis. There are two different cases. The first is that one single water mass is larger than 100\% and other water masses are all 0\%. This mostly happens in the Central Waters (\( \gamma < 27.10 \text{ kg m}^{-3}, \text{Figure 2} \)). The reason is that the key properties, for instance CT, of Central Waters are variable. When the CT increases beyond the range of this water mass, the OMP analysis considers the fraction is over 100\%. In this case, all such samples are considered to be 100\% after confirming the absence of any other water mass. The second case is that none of each single water mass is more than 100\% but the total fraction is more than 100\% when added together. In this study, the total fraction is mostly fractions are generally less than 105\% (\( \gamma > 27.10 \text{ kg m}^{-3}, \text{Figure 2} \)).

In order to map the distributions of water masses, all GLODAPv2 data in the Atlantic Ocean (below the mixed layer) are analyzed with the OMP method by using 6 key properties. In order to solve the contradiction between the limitation of water masses in one OMP run (no more than 5, see Section 2.3.2) and the total number of 16 water masses (Figure 3), the Atlantic Ocean is divided into 17 regions (Table 1) and each with its own OMP run, by only including water masses that are likely to appear in the area. In the vertical, neutral density intervals are used to separate boxes. In the horizontal direction, the division lines are 40°N, the equator and 50°S where the area south of 50°S is one region, independent of density, and additional divisions are set between equator and 40°N (\( \gamma > 26.70 \text{ and 27.30 kg m}^{-3}, \text{latitude of 30°N, Table 1} \)). In this way, we end up with a set of 17 different OMP formulations.
that are used for estimating the fraction(s) of water masses in each water sample. The neutral density
and the latitude of the water sample are thus used to determine which OMP should be applied (Table 1).
Note that all water masses are present in more than one OMP so that reasonable (i.e. few are more than
120% smooth) transitions between the different areas can be realized.

Overview of the water masses in the Atlantic Ocean and the Criteria of Selection

In line with the results from Emery and Meincke (1986) and from our interpretation of the observational
data from GLODAPv2, the water masses in the Atlantic Ocean are considered to be distributed in four
main isopyncal (vertical) layers (Figure 3)—separated by surfaces of equal (neutral) density. (Figure 4).
The Upper Layer is the upper (shallowest) layer with lowest potential neutral density under consideration
and is located within upper –500–1000 m—1000 m of the water column (below the mixed layer, \( \sigma_\theta \) and
\( \gamma < 27.0010 \text{ kg/m}^3 \)). The Intermediate Layer is located between ~1000 m
and 2000 m (between 27.0010 and 27.2000 \text{ kg/m}^3 ). The Deep Deep and
Overflow layer occupies the layer roughly between ~2000 m–4000 m (between 27.7090 and 27.8828.10 kg/m3)
whereas the Bottom Layer is the deepest layer below the deep layer and mostly located below ~4000 meters depth (\( \gamma > 28.10 \text{ kg/m}^3 \)).

In this section, to identify the main water masses in the Atlantic Ocean are identified in each of the four
layers. In Table 2, the determination of their formation areas is the first step (Figure 5) and then the
selection criteria are listed to define SWTs in based on the T—S distribution, pressure (P), potential
temperature (\( \theta \)) or neutral density (\( \sigma_\theta \)) (Table 2). For some SWTs, key additional properties
such as absolute salinity, (SA), oxygen or silicate are necessary in addition to S, \( \theta \) and P in order to
define also required for the water masses. These criteria, which are taken from the
literature and are used to align with previous work also based on defining data from GLODAPv2 product,
the SWTs of all the main water masses. With these criteria, we can narrow down the distribution of
properties for each water mass be defined for further estimating their distributions in the Atlantic Ocean
by using OMP analysis.

For the water masses in the upper layer, i.e. the central waters, an additional step is necessary, to the
Central Waters, properties cover a “wide” range instead of a “narrow” point value due to their variations,
especially in temperature (CT) and salinity (SA). i.e. The Central Waters are labeled by two SWTs to
identify the upper and lower boundaries of properties (Karstens and Tomczak, 1997; 1998). In order
to determine the distribution ranges of each parameter since these water masses occupy the thermocline
and typically cover a wide range for all properties. Here we follow the method developed by (Karstens
and Tomczak, 1997; 1998). One parameter (for instance potential temperature) two SWTs, one property
is taken as a benchmark (neutral density in this investigation) and the relationships between other
parameters to the others are plotted to make a linear fit and finally to find out the ranges of all parameters.
the two endpoints are selected as the criteria of selection. In our investigation, potential density is used as the benchmark (Figure 4) instead of potential temperature since density plays a more significant role in the vertical stratification. This way we define a range for the variable within each water mass, SWTs to label Central Waters (Figure 6).

During the narrative determination of each water mass we display four SWT, two figures are displayed to characterize them—1) Maps where all GLODAPv2 station locations are marked as light grey dots, including a) Depth profiles of the 6 key properties under consideration (same color coding), and stations within the area of formation that we consider are marked in red and stations with any b) Bar plots from the distributions of the samples within the desired properties as defined by Table 2 in blue. 2) The T-S relationship with the same color coding, 3) Depth profiles of the 6 variables under consideration (same color coding), and 4) Bar plots of the distribution of the samples within the criteria (the blue dots in Figure 6 and 7) for a SWT. In the bar-plot, with a Gaussian curve is added to show the statistic results (the mean value and standard deviation) to the selected data (blue dots), and the amplitude of the curve is set to be 2/3 of the highest bar statistics (Figure 7). The plots of properties vs pressure provides an intuitive understanding of each SWT compared to other other WMs in the same region. The distributions of properties distribution with the Gaussian curve will be helpful curves are the basis to visually determine and confirm the SWT property values and associated standard deviations.

Most water masses maintain their original characteristics from their formation areas. However, it is some are worthy to mention that there are also some water masses, especially in the deep and bottom layer, which are be mentioned as products from mixing of several original water masses (for instance, North Atlantic Deep Water is the product from Labrador Sea Water, Iceland-Scotland Overflow Water and Denmark Strait Overflow Water). Also, characteristics of some water masses changes sharply during their pathways (for instance, namely, the sharp drop silicate concentration of Antarctic Bottom Water after passing the equator). As a result, it is unnecessary to redefine these water masses their SWTs. In order to distinguish such water masses from the other original water masses, these are defined specific areas are mentioned as “redefining” areas instead of formation areas, because these water masses, strictly speaking, they are not “formed” in these areas.

In this section, the horizontal (map views) and vertical (sections) distributions of the main water masses are also displayed. On the maps of horizontal view, fractions of water masses are plotted at each station with the interpolated format at their core densities. In order to avoid large interpolation errors, a station is considered as without data and plotted as grey rather than colored dots if there is no data within ±0.1 kg/m² from core density. To exemplify the vertical distribution of the water masses, sections from five selected WOCE/GO-SHIP cruises, which together provide a reasonable representation of the Atlantic Ocean, are displayed (Figure 2 right panel). The A16 section, covering the full north-south extent of the Atlantic Ocean (Expocodes: 33RO20130803 & 33RO20131223), shows the meridional overview of all the main water masses. The A03 (Expocode: 74AB200050501) and A10 (Expocode: 33RO20110906)
sections displays the zonal distribution of the water masses in the North (A03) and South (A10) Atlantic separately. The A25 (Expocode: 06MM20060523) section is located at a relative higher latitude region compared to the A03 section and better represent the deep and overflow waters in particular. From this cruise, we focus on the investigation of LSW, ISOW and DSOW, with the purpose to show the origin of upper and lower NADW. The SR04 (Expocode: 06AQ20101128) is a section in the Antarctic region near Weddell Sea with certain significance to show the origin and formation of AABW. We also show a rough overview figure illustrating the main currents in that density layer, and with the main formation region of each water mass indicated as striped boxes.

4 The Upper Layer, Central Waters

The Upper Layer upper layer is occupied by four water masses called Central Waters that are known to be formed by winter subduction. Central Waters have upper and lower boundaries instead of point values. Statistics are done for all the figures, values between boundaries are and statistics are done to calculate the mean and standard deviations and plotted as the other deep water masses. However, in the further OMP analysis, all the values between the boundaries are considered as Central Waters, that means each Central Water (Figure 7 and Figure 1—4 in Supplement) and occupies two "positions" in selected one OMP analysis run.

Central Waters can be easily recognized by their linear T—S relationships (Pollard et al., 1996, Stramma & England, 1999). In this study, the Upper Layer upper layer is defined to be located above the potential neutral density isoline of 27.010 kg/m³ (below the mixed layer). The formation and transport of the Central Waters are influenced by the currents in the upper layer and finally form relative distinct bodies of water in both the horizontal and vertical directions (Figure 8). The concept of Mode Water is a similar definition in the Upper Layer but referred to as the sub-regions of Central Water, which describes the particularly uniform properties of seawater within the upper layer and more refers to the physical properties (e.g., such as: T—S relationship and potential vorticity). In this study, the unified name "Central Water" which more refers to the biogeochemical properties (Cianca et al., 2009; Alvarez et al., 2014), is used in our study to avoid possible confusions (Cianca et al., 2009, Alvarez et al., 2014).

4.1 Eastern North Atlantic Central Water (ENACW)

The main upper layer water mass in 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 is subducted in the rear west of Iberian Peninsula. One component of the Subpolar Mode Water (SPMW) is carried south and contributes to the properties of ENACW (McCartney & Talley, 1982). In Figure 5, the linear T-S distribution of ENACW can be clearly seen, consistent with Pollard et al. (1996) and the definition of ENACW in Garcia-Ibanez et al. (2015). In Garcia-Ibanez et al. (2015), there is another definition ENACW, but water samples show a discrete distribution warmer than 16 °C by GLDAPv2...
data set in this region, so also samples with potential temperature below 16 °C are selected in this study. As shown in Figure 5, ENACW dominates the upper 500 m depth. The main character of ENACW is the large potential temperature and salinity ranges and low nutrients (especially low in silicate). The work of Pollard et al. (1996) constitutes the main theoretical basis of our analysis. The region limited by latitudes between 39 and 48 °N and longitudes between 15 and 25 °E (east of Mid-Atlantic Ridge), is considered as the formation area of ENACW. Based on the work of Pollard and Pu (1985), potential density, $\sigma_\theta = 26.50 \text{ kg/m}^3$ as higher boundary and $\sigma_\theta = 27.30 \text{ kg/m}^3$ are selected as the lower boundary to define ENACW.

### 4.2 Western North Atlantic Central Water (WNACW)

Western North Atlantic Central Water (WNACW) is another water mass formed through winter subduction (McCartney & Talley, 1982, Worthington, 1959). WNACW is formed at the southern flank of the Gulf Stream (Klein & Hogg, 1996) and is in some literature referred to as 18 ° water since a potential temperature of around 18 °C is one significant feature of this water mass (Talley & Raymer, 1982). In general, seawater in the Northeast Atlantic has higher salinity than in the Northwest Atlantic due to stronger winter convection (Pollard & Pu, 1985) and input of MOW (Pollard et al., 1996, Prieto et al., 2015). However, for the central waters, the situation is the opposite. WNACW has a significantly higher salinity than ENACW by 0.9 PSU units. In this study, we follow McCartney and Talley (1982) and consider the region 24-37°N, 50-70°W as the formation area and pressure less than 1000 m. By defining the depth of WNACW, 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, the constraint is added that concentrations of phosphate lower than 0.3 and silicate lower than 3 $\mu$mol kg$^{-1}$. The properties of WNACW are shown in Figure 5. 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 around 18 °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.

### 4.3 The main Central Water in the region east of the Mid-Atlantic-Ridge (MAR) is the East North Atlantic Central Water (ENACW, Harvey, 1982). This water mass is formed in the inter-gyre region during the winter subduction (Pollard and Pu, 1985). One component of the Subpolar Mode Water (SPMW) is carried south and contributes to the properties of ENACW (McCartney and Talley, 1982).

The inter-gyre region limited by latitudes between 39 and 48 °N and longitudes between 20 and 35 °W (Pollard et al., 1996) is considered as the formation area of ENACW (Figure 5). Neutral densities of 26.50 and 27.30 kg m$^{-3}$ are selected as the upper and lower boundaries to define the SWT of ENACW (Cianca et al., 2009, Prieto et al., 2015), which is also in contrast to Garcia-Ibanez et al. (2015) that used potential temperature (θ) as the upper limit. The core of ENACW is located within the upper 500 m
depth (Figure 7, a) with the iconic linear T-S relationship (Figure 6, b) consistent with Pollard et al. (1996). The main character of ENACW is the large ranges of temperature (CT) and salinity (SA) and low nutrient concentrations, especially silicate (Figure 7, b).

4.2 Western North Atlantic Central Water (WNACW)

Western North Atlantic Central Water (WNACW) is another water mass formed through winter subduction (Worthington, 1959; McCartney and Talley, 1982) with the formation area at the southern flank of the Gulf Stream (Klein and Hogg, 1996). In some studies, this water mass is referred to as 18 °C water since a potential/conservative temperature of around 18 °C is one symbolic feature (e.g. Talley and Raymer, 1982; Klein and Hogg, 1996). In general, seawater 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 MW (Pollard et al., 1996; Prieto et al., 2015). However, for the Central Waters, the situation is the opposite. WNACW has a significantly higher salinity (SA) by ~0.9 g kg⁻¹ than ENACW (Table 4).

In this study, work from McCartney and Talley (1982) is followed and the region 24—37°N, 50—70°W is considered as the formation area (Figure 5) with depth less than 500 m. By defining the SWT of WNACW, neutral density between 26.20 and 26.70 kg m⁻³ is selected since the discrete T—S distribution outside this range (Table 2). Besides the linear T—S relationship, another property of this water mass is, as the alternative name suggests, a conservative temperature around 18 °C, which is the warmest in the four Central Waters due to the lowest latitude of formation area and the impact from the warm Gulf Stream (Cianca et al., 2009; Prieto et al., 2015). In addition, low nutrient is also a significant property compared to other Central Waters (Figure 2 in Supplement).

4.3 Eastern South Atlantic Central Water (ESACW)

The formation area of ESACW is located in area southwest of South Africa and south of the Benguela Current (Peterson and Stramma, 1991). In this region the Agulhas Current brings water from the Indian Ocean (Deruijter, 1982; Lutjeharms and van Ballegooeyen, 1988) that mixes with the South Atlantic Current from the west (Stramma and Peterson, 1990; Gordon et al., 1992). The origin of ESACW can partly be tracked back to the WSACW, but defined as a new SWT since seawater from Indian Ocean is added by the Agulhas Current. The mixing region of Agulhas Current and South Atlantic Current (30—40 °S, 0—20 °E) is selected as the formation area of ESACW (Figure 5). To investigate the properties of ESACW, results from Stramma and England (1999) is followed and consider 200—700m as the core of this water mass. For the properties, neutral density (γ) between 26.00 and 27.00 kg m⁻³ and oxygen concentration higher than 230 µmol kg⁻¹ are used to define ESACW (Table 2). Similar as ENACW, ESACW also exhibits relative large CT and SA ranges 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 (Figure 3 in Supplement).
4.4 Western South Atlantic Central Water (WSACW)

The WSACW is formed in the region near the South American coast between 30 and 45 °S, where surface South Atlantic Current brings central water to the east (Kuhlbrodt et al., 2007). The WSACW is formed with little directly influence from other central water masses (Stramma & 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 & Stramma, 1991). This water mass is a product of three mode waters: the WSACW is formed with little directly influence from other Central Water mass (Sprintall and Tomczak, 1993; Stramma and England, 1999), while the origin of other Central Waters (e.g. ESACW or ENACW) can be traced back, to some extent at least, 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 Subantarctic 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 area of WSACW. We choose potential density (\(\sigma_\theta\)) between 26.0 and 27.0 kg/m^3 and salinity higher than 34.5 for defining m-3 is selected to define the SWT of WSACW. In addition to the physical properties we used and the requirement of silicate concentrations lower than 105 µmol kg^-1 and oxygen concentrations lower than 230 µmol kg^-1 to define this SWT is also added (Table 2). WSACW shows the similar hydrochemical properties to other Central Waters such as linear T-S relationship with large T and S ranges and low concentration of nutrients, especially silicate (Figure 4 in Supplement).

The temperature distribution in this region indicates another peak in the abundance (histogram) for potential densities higher than 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.

4.4 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 and spreads to the north along the Benguela Current (Petersen & Stramma, 1991). In this region the Agulhas Current brings water from the Indian Ocean (Deruijter, 1982, Lutjeharms & van Ballegooyen, 1988) that meets and mixes with the South Atlantic Current (Gordon et al., 1992, Stramma & Peterson, 1990) from the west. 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 ($\sigma_\theta$) between 26.00 and 27.20 kg/m³ and oxygen concentration between 200 and 240 µmol kg⁻¹ are used to define ESACW.

Figure 5 clearly shows the linear T-S relationship for potential density ($\sigma_\theta$) between 26.00 and 27.20 kg m⁻³, which is consistent with the general property of Central Waters (Harvey, 1982, Alvarez et al., 2014, Emery & Meincke, 1986). As shown in Figure 5, 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.

4.5 Atlantic Distribution of Central Waters

Based on our OMP analysis on the GLODAPv2 data product, we can now describe the physical extent of the central waters. Central Waters can be described over the Atlantic Ocean. The horizontal distributions of four main water masses, Central Waters in the Upper Layer, are shown on the maps in Figure 68 and the vertical distributions along selected GO-SHIP sections are found in Figure 7. In general, the eastern central waters, both Central Waters, have higher potential densities, and are thus found deeper, compared to western central waters. This can be seen well in Figure 7, where the difference in the eastern variations being denser, so that the there is significant overlap in the horizontal distribution. The vertical extent of the eastern Central Waters is clearly seen in Figure 9.

The East North Atlantic Central Water (ENACW) is mainly found in the northeast part of North Atlantic, near the formation area off the Iberian Peninsula-inter-gyre region (Figure 8). High fractions of ENACW is also found in a band across the Atlantic at around 40 °N, where the core of this water mass is found close to 1000 m depth in the western part of the basin, (Figure 2-9).

The West North Atlantic Central Water (WNACW) is predominantly found in the western basin of the North Atlantic in an east-west zonal band between ~10 °N and 40 °N, (Figure 6.8). The vertical extent of WNACW is significantly higher in the western basin with an extent of about 500 meter in the west, tapering off towards the east, (Figure 2-9).

The East South Atlantic Central Water (ESACW) is found over most of the South Atlantic, as well as in the tropical and subtropical north Atlantic, (Figure 8). The extent of ESACW do reach particular far north in the eastern part of the basin where it is an important component over the Eastern Tropical North Atlantic Oxygen Minimum Zone, roughly south of the Cape Verde Islands, (Figure 8). In the vertical direction, the ESACW is located below WSACW (Figure 9).

The horizontal distribution of the West South Atlantic Central Water (WSACW) is similar to does also reach into the ESACW, although in the northern hemisphere but is, obviously, concentrated in the western
basin (Figure 8). In the vertical scale, the WSACW is not dominant in the South East Atlantic off Africa. Although both central waters in the south Atlantic have similar horizontal extent, the WSACW dominates also tends to dominate the upper layer of the South Atlantic, above the ESACW—(Figure 2.9).

5 The Intermediate Layer

The intermediate water masses have an origin in the upper 500m of the ocean and subduct into the intermediate depth (1000—1500m) during their formation process. Similar to the upper layer Central Waters, the distribution of the intermediate water masses Intermediate Waters are significantly influenced by the major currents. (Figure 10, left). The potential neutral density ($\sigma_\theta$) of the intermediate water masses is in general between 27.0010 and 27.2090 kg m$^{-3}$, which is our and selected as the definition of the intermediate layer Intermediate Layer.

In the Atlantic Ocean, two main intermediate water masses are found: Subarctic Intermediate Water (SAIW) that originates from the north and Antarctic Intermediate Water (AAIW) that originates from the south (Figure 9). Both water masses are found to be formed in the surface of sub-polar regions in north and south hemisphere respectively. In addition to AAIW and SAIW, Mediterranean Overflow Water (MOW/MW) is also considered as an intermediate water mass inflow to the north Atlantic since the MOW occupies a similar density range as AAIW and SAIW, although the formation history is different. (Figure 10).

5.1 Antarctic Intermediate Water (AAIW)

The Antarctic Intermediate Water (AAIW) is the main water mass in the intermediate depth of the South Atlantic Ocean. This water mass originates from the surface region north of the Antarctic Circumpolar Current (ACC) in all three sectors of the Southern Ocean, in particular in the area east of the Drake Passage in the Atlantic sector (McCartney, 1982, Alvarez et al., 2014). After formation, the AAIW subducts and spreads northward along the continental slope of South America (Piola & Gordon, 1989). The AAIW covers most of the Atlantic Ocean until 40°N and the percentage shows a decrease trend to the north (Kirchner et al., 2009). 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). The two main characteristic features of AAIW is low salinity and high oxygen concentration (Stramma & 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 water masses, including SACW in the north and NADW in the deep, there are several slightly different definitions. The Antarctic Intermediate Water (AAIW) is the main Intermediate Water in the South Atlantic Ocean. This water mass originates from the surface region north of the Antarctic Circumpolar Current (ACC) in all
three sectors of the Southern Ocean, in particular in the area east of the Drake Passage in the Atlantic sector (McCarty, 1982; Alvarez et al., 2014), then subducts and spreads northward along the continental slope of South America (Piola and Gordon, 1989).

Based on the work by Stramma and England (1999) and Saenko and Weaver (2001), the region between 55 and 40 °S (east of the Drake Passage) at depths below 100 m is selected as the formation area of AAIW as well as the primary stage during the subduction and transformation (Figure 5). Previous work is considered to distinguish AAIW from surrounding water masses, including SACW in the north and NADW in the deep. Piola and Georgi (1982) and Talley (1996) define AAIW to have potential densities ($\sigma_\theta$) between 27.00–27.10 and 27.40 kg/m$^3$. On the other hand, $\sigma_\theta$ and Stramma and England (1999) define the boundary between AAIW and SACW at $\sigma_\theta = 27.00$ kg/m$^3$ and the boundary between AAIW and NADW at $\sigma_\theta = 32.15$ kg/m$^3$. Furthermore, we used these $\sigma_\theta$ as criteria to define AAIW: potential neutral density between 26.95 and 27.50 kg/m$^3$ and pressure less than 100 and 300 bar. In addition, high oxygen (> 230–260 µmol/kg) as being important to distinguish AAIW from Central Waters (WSACW and ESACW), while the relative high potential temperature (> 0.5 °C) and low silicate concentration (< 30 µmol/kg) are additional trade marks of boundary to differentiate AAIW that we use to distinguish between AAIW and AABW. As shown in Figure 8, (Table 2). The AAIW covers most of the AAIW samples in the Atlantic Ocean until ~30 °N and the percentage shows a potential density decrease trend to the north (Kirchner et al., 2009) at the depth between $\sigma_\theta = 27.00–27.40$ kg/m$^3$. The characteristics of AAIW show low salinity, and high oxygen and low silicate concentrations compared to SACW and NADW, and low potential temperature (< 3.5 °C) (Talley, 1996) (Figure 5 in Supplement, Stramma and England, 1999).

5.2 Subarctic Intermediate Water (SAIW)

The Subarctic Intermediate Water (SAIW) originates from the surface layer of the North Atlantic Subpolar Gyre, along the Labrador Current (Lazier & Wright, 1993, Pickart et al., 1997). This water mass subducts and spreads southeast in the region north of the NAC, advects across the Mid-Atlantic-Ridge and finally interacts with MOW (Arhan & King, 1995, Arhan, 1990). MOW (Arhan, 1990, Arhan and King, 1995). This formation of SAIW is a 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), (Read, 2000; Garcia-Ibanez et al., 2015). In Garcia-Ibanez et al. (2015), there are two definitions of SAIW, SAIW$_a$, which is biased to the warmer and saltier NAC, and SAIW$_b$, which is closer to the cooler and fresher Labrador Current. In this study, we discuss Here.
only the combination of these two end-members when considering is considered in the whole Atlantic Ocean scale study.

For defining the spatial boundaries we followed Arhan (1990) and choose longitudes selected the region 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 8). Within this area we follow Read (2000), and choose potential neutral densities higher than 27.65 kg m\(^{-3}\) and potential conservative temperature higher than 4.5 °C to define SAIW. Similar to the definition of AAIW, we include samples by following Read, (2000). Samples in the depth range from the MLD to 500 m are investigated as the core layer of SAIW; this pressure includes, which included the formation and subduction of SAIW. (Table 2).

In the T-S relationship (Figure 8), the mixing of two main sources, the warmer and saltier NAC and the colder and fresher Labrador Current, is evident. In Figure 8, we can see that this water mass is characterized by relatively low potential temperature, salinity and silicate concentration, but is high in oxygen.

### 5.3 Mediterranean Overflow Water (MOWMW)

The predecessor of the Mediterranean Overflow Water (MOWMW) is the Mediterranean Overflow Water (MOW) flowing out through the Strait of Gibraltar, whose main component is the modified Levantine Intermediate Water. This water mass is recognized by high salinity and temperature and intermediate potential neutral 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 & Price, 1997). In Gulf of Cadiz, the outflow of MOW mixes rapidly with the overlying ENACW leading to a sharp decrease of salinity and forms the MW (Baringer and Price, 1997). In Gulf of Cadiz, the outflow of MW 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, 1979, Reid, 1978). (Reid, 1978; 1979). The impact from MW is significant in almost the entire Northeast Atlantic in the Intermediate Layer (east of the MAR, Figure 7 in Supplement), with high conservative temperature and absolute salinity but low nutrients compared to other water masses.

Here we follow Baringer and Price (1997) and define MOW to be an independent water mass represented by the high salinity (salinity between 36.35 and 36.65) samples with the formation area west of the Strait of Gibraltar (Figure 8). The Mediterranean water is characterized by salinity higher than 38.4. Almost the entire Northeast Atlantic intermediate layer, east of the MAR, is influenced by MOW. As the most characteristic property of MOW is the high salinity, we display a salinity section plot (Figure 8).
8) of A03 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 8. 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 are shown in Figure 8 and Table 4. The SWT of MW by the high salinity (absolute salinity between 36.5 and 37.00 g kg\(^{-1}\), Table 2) samples in the formation area west of the Strait of Gibraltar (Figure 5).

5.4 Atlantic distributions

Distributions of Intermediate Waters

A schematic of the main currents in the intermediate layer (\(\sigma_\theta\) between 27.10 and 27.290 kg m\(^{-3}\)) is shown in Figure 9 (left panel).

The Subarctic Intermediate Water (SAIW) is mainly found north of 40\(^{\circ}\) N in the eastern basin, whereas the distribution of SAIW in the western basin is further south, Figure 9 west basin by mixing of two main sources, the warmer and saltier NAC and the colder and fresher Labrador Current and characterized with relative low CT (< 4.5 °C), SA (< 35.1 g kg\(^{-1}\)) and silicate (< 11 \(\mu\)mol kg\(^{-1}\)). The SAIW and MOW has similar densities (although the density range of MOW is slightly higher) but MW can be easily distinguished based on the six variables used by the OMP analysis, and Figure 9 shows the east/west transition between these two water masses east of MAR. Similarly, the north/south transition between these due to significantly different properties. The meridional distributions of three intermediate water mass, Intermediate Waters along the A16 section is nicely illustrated in Figure 9, where are shown in Figure 10 (upper panel) as well as the zonal distributions of SAIW and MOW along the A03 section. A “blob” of MW centered around 35°N separate can be seen to separate the AAIW from the SAIW in the eastern basin. North Atlantic. The fractions of SAIW in the western basin are definitely higher (Figure 10, right).

The Mediterranean Overflow Water (MOW) The MW enters the Atlantic from Strait of Gibraltar and spreads in two branches to the north and the west. MOW is mainly close to its entry point to the Atlantic, the Gulf of Cadiz, but with significantly higher fractions of MOW found in the western basin. North Atlantic. The distribution of MOW can be seen as roughly following the two intermediate pathways following two branches (Figure 10, left). One branch spreads to the north into the West European Basin until ~50°N, while the other branch spreads in a westward direction past the MAR (Figure 11), mainly at latitudes between 30 and 40° N. The density of MOW is similar to that of SAIW, and the distributions of the two water masses are complementary in the North Atlantic (Figure 10, right).

The Antarctic Intermediate Water (AAIW) has a southern origin and is found at slightly lighter densities (core \(\rho\) density ~27.220 kg m\(^{-3}\), Figure 10, right) compared to MOW, SAIW, and AAIW, Figures 9 and 10. The AAIW is formed in the region south of 40° S where it sinks and spreads to...
the north at depth between ~1000 and 2000 m at potential neutral densities between 27.410 and 27.920 kg m$^{-3}$. In the South Atlantic, the $\theta$- $\sigma_t$ relationship is nearly isopycnal. The AAIW is the only Intermediate Layer water mass that is formed through winter deep convection in the Labrador and Irminger Basins (Stramma et al., 2004; Tanhua et al., 2005) (Stramma et al., 2004; Tanhua et al., 2005). The Labrador Sea Water (LSW) is formed through winter deep convection in the Labrador and Irminger Basins (Stramma et al., 2004; Tanhua et al., 2005) (Stramma et al., 2004; Tanhua et al., 2005). These two water masses meet and mix in the Denmark Strait Overflow Water (DSOW) and the Iceland-Scotland Overflow water (ISOW) originate from Arctic Ocean and the Nordic Seas and mainly enter the North Atlantic through either the Denmark Strait of the Faroe Bank Channel. (Figure 12, left). In the North Atlantic, these two water masses sink, mainly following the topography. These two water masses meet and mix in the Irminger Basin (Stramma et al., 2004; Tanhua et al., 2005). The Labrador Sea Water (LSW) is formed through winter deep convection in the Labrador and Irminger Seas, and makes up the bulk of the upper North Atlantic Deep Water (uNADW). Due to intense mixing processes we define the LSW, DSOW and ISOW as defined as the water masses in north of 40 °N whereas south of this latitude we consider the presence of the two variations of NADW, are considered (Figure 12, right).

From the formation area, in south of 40 °N, both variations of the NADW spread, south mainly with the Deep Western Boundary Current (DWBC, Figure 12, left) (Dengler et al., 2004), through the Atlantic until ~50 °S where they meet the Antarctic Circumpolar Current (ACC). During the southward transport, the NADW also spreads significantly in the zonal direction, so that we can find NADW in the whole Atlantic basin at those densities (Lozier, 2012), so that the distribution of NADW covers mostly the whole Atlantic basin in the Deep and Overflow Layer (Figure 12, right). The southward flow of NADW in the North Atlantic, is also an indispensable component of Atlantic Meridional Overturning Circulation (AMOC) (Broecker & Denton, 1989; Elliot et al., 2002; Lynch-Stieglitz et al., 2007; Broecker and Denton, 1989; Elliot et al., 2002; Lynch-Stieglitz et al., 2007).

### 6.1 Labrador Sea Water (LSW)
As an important water mass by its own virtue and for that contributes to the formation of North Atlantic Deep Water (NADW), Labrador Sea Water (LSW) is predominant in mid-depth (between 1000m and 2500m depth) in the Labrador Sea region (Elliot et al., 2002). The LSW is formed in the region of Labrador Sea by deep convection during winter (Clarke & Gascard, 1983), and is typically found at mid-depth with $\sigma_\theta = 27.77$ kg/m$^3$. This water mass was noted by (Wüst & Defant, 1936) this water mass was firstly noted by (Wüst and Defant, 1936) due to its salinity minimum and later defined and named by Smith et al. (1937). The LSW is formed by deep convection during the winter and is typically found at depth with $\sigma_\theta = 27.77$ kg m$^{-3}$ (Clarke and Gascard, 1983). Since then the character has been identified as a contribution to the driving mechanism of northward heat transport in the Atlantic Meridional Overturning Circulation (AMOC) (Rhein et al., 2011). The LSW is characterized by relative low salinity (lower than 34.9) and high oxygen concentration (~290 µmol/kg) (Talley & Mccartney, 1982). Another important criterion of LSW is the potential density ($\sigma_\theta$), that ranges from 27.68 to 27.88 kg m$^{-3}$ (Stramma et al., 2004, Kieke et al., 2006). In the large spatial scale, LSW can be considered as one water mass (Dickson & Brown, 1994), however significant differences of different “vintages” of LSW exist (Kieke et al., 2006, Stramma et al., 2004). LSW can broadly be kg$^{-1}$ (Talley & Mccartney, 1982). Another important criterion of LSW is the potential density ($\sigma_\theta$), that ranges from 27.68 to 27.88 kg m$^{-3}$ (Clarke and Gascard, 1983; Gascard and Clarke, 1983; Stramma et al., 2004; Kieke et al., 2006). 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 exist (Stramma et al., 2004; Kieke et al., 2006). In some references, this water mass is also broadly 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$^{-3}$ (Smethie & Fine, 2001, Kieke et al., 2006, Kieke et al., 2007; Smethie and Fine, 2001, Kieke et al., 2006; 2007). The LSW is considered as the main origin of the upper NADW (Talley & Mccartney, 1982, Elliot et al., 2002). On the basis of the above work, the formation area of LSW is selected to include the Labrador Sea and Irminger Basin west of Mid-Atlantic Ridge. For the purpose of our analysis, we use the whole scale of the Atlantic Ocean and Greenland; we consider LSW as one integral water mass. Although the region between Labrador Sea is located in North Atlantic between the Labrador Peninsula and Greenland, for this analysis we consider the formation region of LSW to include and parts of the Irminger Basin (Figure 11). Within this geographical region we follow the definition from (5). The neutral density (γ) between 27.70 to 28.10 kg m$^{-3}$ as well as low conservative temperature (CT < 4°C) are used to define SWT of LSW (Table 2) by considering Clarke and Gascard (1983) and Stramma and England (1999). Defining LSW as samples with potential density ($\sigma_\theta$) between 27.68 to 27.88 kg m$^{-3}$ (Figure 11) with the depth range of 500-2000m (Elliot et al., 2002).
Trademark characteristics of LSW are relative low salinity and high oxygen concentration. Figure 11 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. (Figure 8 in Supplement).

6.2 Iceland-Scotland Overflow Water (ISOW)

The Iceland Scotland Overflow Water (ISOW) flows close to the bottom from the Iceland Sea to the North Atlantic in the region east of Iceland, mainly through the Faroe-Bank Channel (Swift, 1984, Lacan et al., 2004; Zou et al., 2020). ISOW turn into two main branches when passing the Charlie-Gibbs Fracture Zone (CGFZ), with the first one flowing through the Mid-Atlantic-Ridge, into the Irminger basin, where it meets and mixes with DSOW (Figure 12). The other branch is transported 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 and is characterized by high nutrient and low oxygen concentration. The following criteria, conservative temperature between 2.2 and 3.3 °C and absolute salinity higher than 34.95 g kg\(^{-1}\), are used to define the SWT of ISWO, and neutral density higher than 28.00 kg m\(^{-3}\) is added order to distinguish ISOW from LSW in the region west of MAR (Table 2 and Figure 9 in Supplement).

6.3 Denmark Strait Overflow Water (DSOW)

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. This overflow water mass is considered as the coldest and densest component of the sea water in the Northwest Atlantic Ocean and constitute a significant part of the southward flowing NADW (Swift, 1980). 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 to distinguish DSOW from NEABW, which has a high silicate concentration. As shown in Figure 11, Samples from the Irminger Sea (Figure 5) with neutral density higher than 28.15 kg m\(^{-3}\) (Table 2 and Figure 10 in Supplement) are used for the definition of DSOW (Rudels et al., 2002; Tanhua et al., 2005). DSOW is mostly found close to the bottom 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).

6.3 Iceland-Scotland Overflow Water (ISOW)

The Iceland Scotland Overflow Water, ISOW, flows close to the bottom from the Iceland Sea to the North Atlantic in the region east of Iceland, mainly through the Faroe-Bank Channel (Swift, 1984, Kissel et al., 1997). ISOW turn into two main branches when passing the Charlie-Gibbs Fracture Zone (CGFZ), with the first one flowing through the Mid-Atlantic-Ridge, into the Irminger basin, where it meets and mixes with DSOW. The other branch is transported 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 and is 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/m³. Figure 11 displays our characterization of ISOW in the Iceland Basin, which is consistent from the result in the literature (Garcia-Ibanez et al., 2015).

6.4  Upper North Atlantic Deep Water (uNADW)

The uNADW is mainly formed by mixing of ISOW and LSW, and we consider this to be considered as a distinct water mass south of the Labrador Sea as this region is identified as the redefining area of upper and lower NADW (Dickson & Brown, 1994). We select the (Dickson and Brown, 1994). The region between latitude 40 and 50°N, west of the MAR is selected as the formation area of NADW (Figure 425) and use the criteria of potential neutral density between 27.72 and 27.82 kg/m³ and 28.05 kg m⁻³ and conservative temperature lower than 4.0 °C with depth range from 1200 to 2000 m (Table 2 and Figure 11 in Supplement) to define the SWT of uNADW (Stramma et al., 2004). As a product of mixing mixture from LSW and ISOW, the uNADW obviously inherits many properties from LSW, but is also significantly influenced by the ISOW. The relative high temperature (~3.3 °C) is a significant feature of the uNADW together with relatively low oxygen (~280 µmol kg⁻¹) and high nutrient concentrations, which is a universal symbol of deep water (Table 4).

6.5  Lower North Atlantic Deep Water (lNADW)

We use the same geographic region to define the formation area of lNADW (Figure 5). In this region, the ISOW and DSOW (with some influence of LSW) mix with each other and form the lower portion of NADW (Stramma et al., 2004). Water samples between depths of 2000 and 3000 m with potential CT higher than ~2.5°C and neutral densities between 27.7695 and 27.8281 kg/m³ are selected to define the INADW. From the data shown in Figure 12, lower NADW can be found with properties more similar to ISOW compared with DSOW. For instance, the values of salinity and oxygen concentration are lower than ISOW. For nutrients, the SWT of INADW have almost the same values to ISOW, but the relatively high potential temperature shows that the impact from LSW (Table 2 and Figure 12 in Supplement).

6.6  Atlantic Distributions of Deep and Overflow Waters

The water masses dominate the neutral density interval 27.7–27.88 and 28.05–28.10 kg/m³ in the Atlantic Ocean. Figure 12. In the area north of roughly 40°N the overflow waters dominate the deeper layers as well, except in the eastern basin where a significant contribution from the North East Atlantic Bottom Water (NEABW, section 7). Due to our definition of the water masses, three water masses dominate the region north of 40°N: Labrador Sea Water (LSW), Iceland-Scotland Overflow Water (ISOW) and Denmark Strait Overflow Water (DSOW). In the region south of 40°N the upper and
lower NADW, considered as products from these three original overflow water masses, dominate the deep and overflow layer (Figure 12).

The Labrador Sea Water (LSW) is commonly characterized as two variations, ‘upper’ and ‘classic’ although in this study we consider this as one water mass. The LSW dominates the North West Atlantic Ocean in the characteristic density range. In Figure 12, we choose to display $\gamma = 27.74, \sigma_\theta = 28.05\,\text{kg/m}^3$ that corresponds to the lighter version of the LSW. The LSW spreads east and southward in the North Atlantic Ocean, but is less dominant in the area west of the Iberian Peninsula where the presence of MOW from the Gulf of Cadiz tends to dominate that density level. Note that although the LSW is slightly denser than the MOW, their density ranges do overlap (Figure 12 and 13).

The Iceland-Scotland Overflow Water (ISOW) is mainly distributed in the Northeast Atlantic north 40°N between Iceland and Iberian Peninsula with core at $\sigma_\theta = 27.88, \gamma = 28.05\,\text{kg/m}^3$. The ISOW is also found west of Iceland, in the Irminger and Labrador Seas between the DSOW and LSW (Figure 12 and 13).

The Denmark Strait Overflow Water (DSOW) is mainly found in the Irminger and Labrador Seas as the densest layer close to the bottom. Our analysis indicates a weak contribution of DSOW also east of the MAR. South of the Grand Banks the DSOW is already significantly diluted and only low to moderate fractions are found. Here we consider two new water masses, upper and lower NADW in the region south of 40°N. After passing 40°N, upper and lower NADW, considered as independent water masses (Figure 12 and 13).

After passing 40°N, the upper and lower North Atlantic Deep Water (u/l NADW) are considered as independent water masses and dominate the most of the Atlantic Ocean in this density layer. The map in Figure 12 shows that upper NADW covers the most area, while the lower NADW is found mainly found in the west region near the Deep Western Boundary Current (DWBC), especially in South Atlantic. In the vertical view based on sections (Figure 14), the southward transports of both upper and lower NADW can be seen until ~ 50°S where they meet AABW in the ACC region.

The Bottom Layer and the Southern water masses

We define the 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 22.888 kg/m$^3$ or a silicate concentration in excess of 80 µmol kg$^{-1}$. These water masses have an origin in the Southern Ocean (Figure 15, left) and are characterized by their high silicate concentrations. The Antarctic Bottom Water (AABW) is the main water mass in the bottom layer, and Bottom Layer (Figure 15, right). This water mass 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 (Figure 16), where we define this water mass as new SWT is redefined as North East Atlantic Bottom Water (NEABW). As being due to the drastic change in properties (sharp decrease in silicate concentration). As the two main sources of AABW, CDW and WSBW are confined to the Southern Ocean, (Figure 15, right), so they are referred as the southern water masses and discussed in this section together with bottom waters.

7.1. Antarctic Bottom Water (AABW)

Antarctic Bottom Water (AABW) is the main bottom water mass symbolic Bottom Water in the South whole 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, Figure 15, right) and plays a significant role in the Thermohaline Circulation (Rhein et al., 1998, Andrié et al., 2003). (Rhein et al., 1998; Andrié et al., 2003). 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 & Gammelsrod, 1988). (Foldvik and Gammelsrod, 1988; Alvarez et al., 2014).

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, (Figure 5), with neutral density (γ) larger than 28.27 kg m$^{-3}$ (Weiss et al., 1979, Orsi et al., 1999). (Weiss et al., 1979; Orsi et al., 1999). 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 characteristic property of AABW. The main source region of AABW is the Weddell Sea (Table 2).

In Figure 16, we can see clearly that AABW (blue points) is a mixture of another two original water masses, CDW and WSBW, which are referred to as southern water masses in the next section, in the formation area. This result is also consistent with Orsi et al. (1999) and van Heuven et al. (2011). The first water mass is the CDW with relative warm temperature (CT > 0.4 °C) remnants from CDW, which comes as advected with the ACC from the north. The other one, which is while the extremely cold Shelf Water (θ < -1 °C) comes as Weddell Sea Bottom Water (WSBW) from the south. As shown in Figure 16, we find AABW is found from 1000m to 5500m depth. The characteristic properties of AABW are the (Figure 16 and 17) with low temperature (CT < 0 °C), salinity (SA < 34.68) and high nutrient concentrations, especially the high silicate concentrations. In Figure 16 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. (Figure 13 in Supplement).

7.2. Northeast Atlantic Bottom Water (NEABW)
Northeast Atlantic Bottom Water (NEABW), also called lower Northeast Atlantic Deep Water (NEADW in Garcia-Ibanez et al. (2015)), is mainly found below 4000 m 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 characteristic properties of AABW change significantly on the slow transport north. We choose to define a new SWT for this as a new water mass in the north of the Equator, similar to the formation redefinition of NADW south of the Labrador Sea.

The region following east of the MAR and between the equator and 30 °N, i.e. before NEABW enters the Iberian Basin, is selected as the redefining area of NEABW (Figure 16). We also use the criteria of water samples from a depth deeper than 4000 m and potential temperature CT above 1.8 °C. are also used (Table 2). In the T—S diagram of NEABW (Figure 16) we can see the linear T—S relationship similar to T—S distribution between NEABW and AABW in the Weddell Sea, but with significantly higher potential temperatures and salinities, roughly CT and SA of ~1.95 °C and ~35.060 g kg$^{-1}$, respectively. Most NEABW samples have a potential neutral density higher than 27.8828.10 kg m$^{-3}$, and NEABW is characterized by low potential temperature (θ), low salinity CT and SA, but high silicate concentration. (Figure 14 in Supplement). This shows further suggests that NEABW originates from AABW, although most properties have been changed significantly from the origin in the South Atlantic.

### 7.3 Circumpolar Deep Water (CDW) / Warm Deep Water (WDW)

Circumpolar Deep Water (CDW) or, as it is also called, Warm Deep Water (WDW), which has significance to the thermohaline circulation during the wind-driven upwelling in the Southern Ocean (Morrison et al., 2015), is the lighter of the two water masses that constitute AABW. In our study, we consider the formation. The production of this water mass that mixes with WSBW directly as CDW (WDW in van Heuven et al. (2011)). CDW is a product from can be tracked to the southward flow of NADW and the large-scale mixing of several water masses in the Antarctic Circumpolar Current (ACC) region (van Heuven et al., 2011). The production 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, (Figure 14, upper panel), this part of NADW mixes with other water masses in the ACC and forms a new water mass. Then this water mass spreads further southward and passes the ACC. We define CDW as a new water mass into the ACC region, where it contacts with other water masses, including AAIW above and AABW below. After passing the ACC region, CDW splits into two branches at ~60 °S. The upper branch is upwelled and partly joint into the AAIW, while the rest spreads towards the coastal region, mixes with the cold fresh shelf water, sinks to the bottom and finally forms the Weddell Sea Bottom Water (WSBW), which is another contribution to the AABW (Marshall and Speer, 2012; Abernathey et al., 2016). The lower branch sinks and mixes with the WSBW below and contributes to the formation of AABW.
In this study, the SWTs of CDW is defined by considering the water samples south of ACC, lower branch, and the region between 55 and 65 °S is selected as the defining formation area. (Figure 5). To specify define SWT of CDW we selected water samples with depth between 200 and 1000 m in this 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 $\sigma_a$ higher than 27.80 kg/m³. The properties of CDW are shown in Figure 17, 34.82 kg/m³ and CT between -0.5 and 1 °C (Table 2). Similar to other bottom/southern SWTs, CDW is characterized also defined 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/m³, and the salinity higher than 34.63 concentrations (Figure 15 in Supplement).

7.4 Weddell Sea Bottom Water (WSBW)

The Weddell Sea Bottom Water (WSBW) is the densest water mass that takes part in the formation of AABW. Similar to CDW, WSBW is also formed in the bottom layer. As mentioned in the Weddell Sea region, relative warm water ($\sigma_a > 0 °C$) flows southward and above section, part of CDW from the upper branch cools down to $\sigma_a$ lower than -1 °C rapidly by mixing with extremely cold shelf water that is transported and sinks down to the bottom along the continental slope. WSBW is thus formed in the Weddell Sea basin below the depth of 3000 m before it meets and mixes with CDW-AABW. Compared with CDW, its low potential, The low temperature of WSBW compared to CDW (CT = -0.8 °C) is a significant characteristic 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⁻¹. The properties of WSBW are shown in Figures 17. In addition to the physical properties, such as low potential temperature and high potential density, WSBW has high nutrient concentrations, but unlike CDW, Water samples in the latitudinal boundaries of 55 - 65 °S in the Weddell Sea (Figure 5) with pressures larger than 3000 m and CT lower than -0.7 °C and silicate higher than 105 µmol kg⁻¹ are selected to define the SWT of WSBW (Table 2), following Gordon (2001) and van Heuven et al. (2011).

WSBW has high oxygen concentration.

7.5 Atlantic distribution of the bottom waters and southern water masses

AABW and NEABW dominate the bottom layer ($\sigma_a > 27.88 > 28.10$ kg/m³). From the aerial view of the map horizontal distribution (Figure 18, 15) it can be seen that AABW and NEABW cover the most bottom area of South and North Atlantic respectively. In fact, both water masses have the same
origin but are distinguished by defining/redefining a new SWT as NEABW due to the sharp reduction of silicate, which is an important signal to label bottom water masses, after passing the equator (Figure 1916). The AABW is formed in the Weddell Sea region south of the Antarctic Circumpolar Current (ACC). After leaving the formation area, AABW sinks to the bottom due to the high density during the way north. After passing the ACC, AABW meets NADW and they have some suffers from water exchange from NADW between 50 °S until AABW reaches the equator (van Heuven et al., 2011). Similar to AABW, NEABW also mainly mixed with lower NADW between equator and 40 °N. North of 40 °N, NEABW meets lower NADW with origins from ISOW (Garcia-Ibanez et al., 2015). Similar to AABW, NEABW also mainly contacts with lower NADW and its origin (ISOW) in the North Atlantic (Garcia-Ibanez et al., 2015).

In the Weddell Sea Region, where the AABW is formed, region, distributions of two initial water masses, CDW and WSBW, mainly reflect the formation process of AABW as displayed based on SR04 sections (Figure 2017). In the zonal section across the Weddell Sea, AABW can be seen as the mixture of CDW and WSBW. The core of CDW distributes in the upper 1000m and WSBW origins from the surface and subducts sinks along the continental slope into the bottom below 4000m. This result is consistent with (van Heuven et al., 2011). Both original water masses meet each other at depth between ~2000 and 4000m, where AABW is formed, with main core locates at ~3000m. The meridional section shows the northward outflow of AABW into the Atlantic Ocean. AABW is located between 2000 and 4000m as a product from CDW and WSBW. After leaving Weddell Sea region, AABW is considered as an independent water mass and spreads further northward as the only bottom water mass until the equator.

8 Conclusions and Discussion

The characteristics of the main water masses in their formation areas are defined in a 76-dimensional hydro-chemical space in the Atlantic Ocean. The values of properties for these water masses form a fundamental basis to investigate their transport, distribution and mixing of water masses and referred to as SWTs. Table 4 and Figure 3 provides an overview of the properties, and the standard deviation of all the 16 Atlantic Ocean main water masses considered in this study. Seven often measured hydro-chemical and physical variables. The distribution of water masses are used to characterize these main SWTs in the Atlantic Ocean. To guide the water masses descriptions, their distributions are estimated by using OMP analysis based on the GLODAPv2 data product, and preliminarily divided into four main vertical layers roughly separated by potential density in the shallow and concentration of silicate in the deep southern Hemisphere based on neutral densities.
The upper layer, which covers the most shallow layer (typically down to about 500 m depth) of the ocean below the mixed layer (the mixed layer is not considered in this analysis), is occupied by central waters. The intermediate layer is situated between the upper layer and the deep and overflow layer at roughly 1000 to 2000 m depth. Of the three water masses in this layer, AAIW and SAIW are both characterized by relative low (absolute) salinity and (conservative) temperature, while the MOW contains high SSA and TCT. The SAIW and MOW are the two main water masses commonly found and show a Northwest-Southeast distribution in the North Atlantic. In the eastern part, MOW overflows from the Mediterranean Sea, across the Strait of Gibraltar and spreads to the north and west. In the South Atlantic, AAIW is the dominate water mass in this layer. After the formation in the shallow layer, AAIW sinks into intermediate depth (around 1000 m) and spreads to the north until ~20° layer of the region south of 30° N, and this water mass can easily be recognized with low salinity. In the deep and overflow layer between roughly 2000 and 4000 m, water masses are found with an origin in the North Atlantic. NADW is the dominate water mass with a relative complex origin from LSW, ISOW and DSOW. The bottom layer is occupied by water mass AABW with a southern origin, defined by low potential temperatures, high densities, and CDW and WSBW. After passing the equator, this water mass is redefined as NEABW due to the changes in properties (silicate concentrations).

Besides the 16 main Atlantic Ocean water masses, additional water masses still exist and can be found in the Atlantic that cannot be explained by the mixing of any above listed original water masses. This tends to happen close to the coast by local oceanographic events, such water masses are not listed and considered as main water mass in this study and also no additional SWTs are defined. For instance, in the coastal region of Southern Benguela Upwelling System (15 – 20° E, 30 – 34°S), water samples are found with low temperature and oxygen (CT = -8 °C, oxygen = ~150 umol kg⁻¹). This cannot be explained by the mixing of ESACW and WSACW, which are the only two possible water masses in this region and depth, because the CT and oxygen of both water masses are higher than these values. One possible explanation is that low-oxygen water is carried by the upwelling from the lower (Flynn et al., 2020).

The here presented characteristics (property values and the standard deviation) of Atlantic Ocean water masses and their distributions of water masses are intended to guide water mass analysis of hydrographic data and expect to provide a basis for further biogeochemical research.

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References


52


