

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 $\mu\text{mol kg}^{-1}$

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

Checked, “the water masses”.

306 (“...our analysi. The region...”),

Checked, “our analysis”.

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

Checked, “being important to distinguish AAIW”.

and 536 (“vintages” of LSW exist), 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.

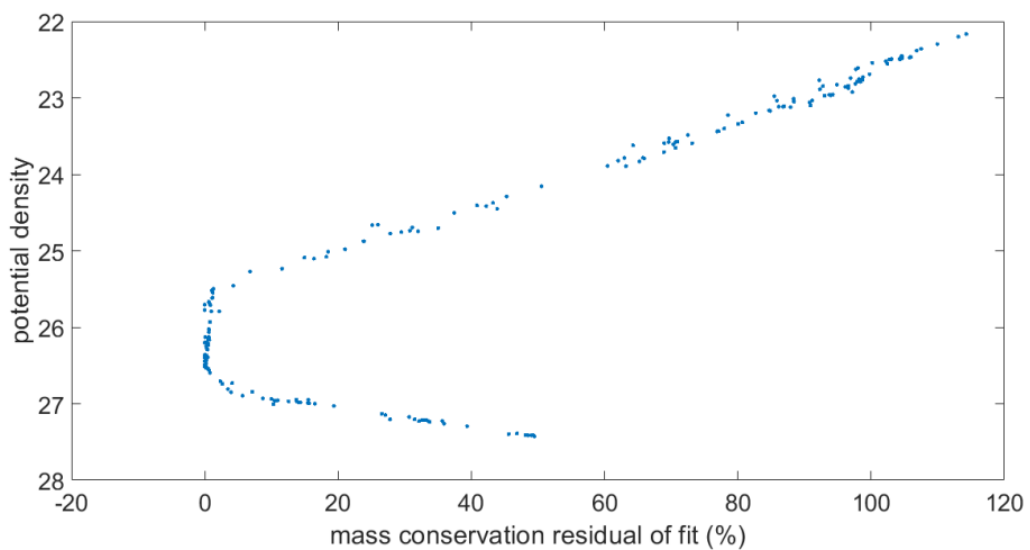
Additional text is added to explain the divisions of OMP runs, including in both horizontal and vertical directions and also the reasons.

- 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.

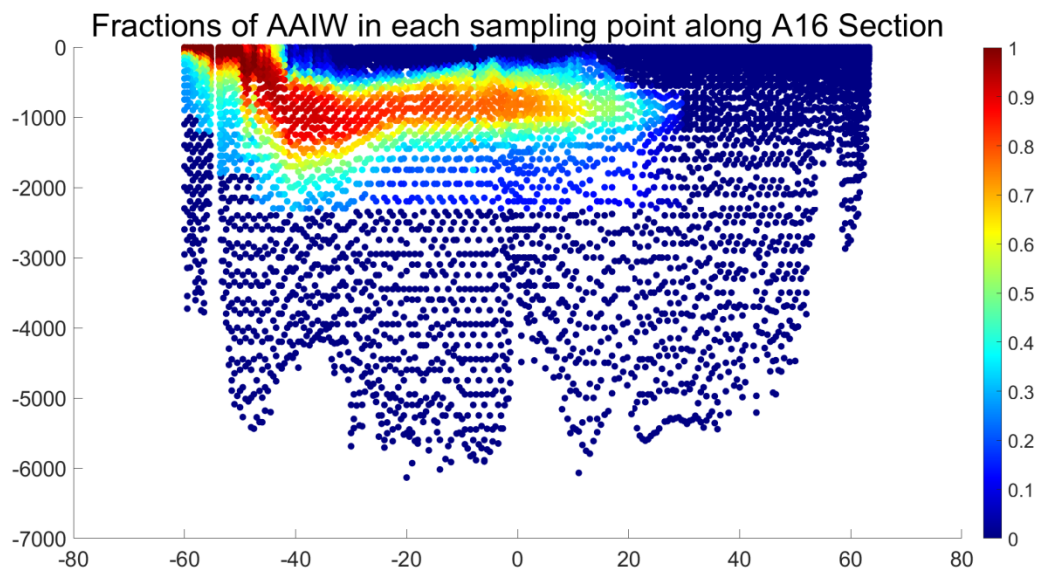
This point is discussed in the same paragraph together with c.

- 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 $\sigma_\theta = 27.00 \text{ kg m}^{-3}$, 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 $\sigma_\theta = 27.00 \text{ kg m}^{-3}$ (new boundary is $\gamma = 27.10 \text{ kg m}^{-3}$) is not because of OMP analysis, but the result from the objmap in the interpolation calculations from all the sampling points.



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 $\sigma_\theta = 27.00 \text{ kg m}^{-3}$ (new boundary is $\gamma = 27.10$), 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 were 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 work 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 re-organization 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 -1°C 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

Carracedo, L.I., Pardo, P.C., Flecha, S., and Pérez, F.F.: On the Mediterranean Water Composition. *J Phys Oceanogr.*, 46, 1339–1358, 2016.

Pollard, R.T., Griffiths, M.J., Cunningham, S.A., Read, J.F., Pérez, F.F., Ríos, A.F.: Vivaldi 1991 – a study of the formation, circulation and ventilation of Eastern North Atlantic Central Water. *Progress in Oceanography* 37, 167–192, 1996.

Unesco: Progress on oceanographic tables and standards 1983–1986: Work and recommendations of the Unesco/SCOR/ICES/IAPSO Joint Panel. Chapter 7.1: Practical Salinity. *Unesco Technical Papers in Marine Science* 50, p. 9, 1986.

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 extend 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 least 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

- Saenko, O. A., and A. J. Weaver (2001), Importance of wind-driven sea ice motion for the formation of antarctic intermediate water in a global climate model, *Geophys. Res. Lett.*, 28(21), 4147–4150, doi:10.1029/2001GL013632.
- Sallee, J.-B., K. Speer, S. Rintoul, and S. Wijffels (2010), Southern Ocean thermocline ventilation, *J. Phys. Ocean.*, 40(3), 509–529, doi:10.1175/2009JPO4291.1.
- Nycander, J., M. Hieronymus, and F. Roquet (2015), The nonlinear equation of state of sea water and the global water mass distribution, *Geophys. Res. Lett.*, 42(18), 7714–7721, doi:10.1002/2015GL065525.
- Abernathey, R. P., I. Cerovecki, P. R. Holland, E. Newsom, M. Mazloff, and L. D. Talley (2016), Water-mass transformation by sea ice in the upper branch of the southern ocean overturning, *Nat. Geosci.*, 9, 596–601, doi:10.1038/ngeo2749.
- Groeskamp, S., R. P. Abernathey, A. Klocker (2016), Water Mass Transformation by Cabeling and Thermobaricity. *Geophysical Research Letters*

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.](#)

1 **~~Characteristics of Water Masses in the Atlantic Ocean based on~~**
2 **~~GLODAPv2 dataset: Characteristics and Distributions~~**
3

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15 **Abstract:** ~~The characteristics of the main~~ water masses are presented in the Atlantic
16 Ocean ~~are investigated and defined~~ knowledge of their distributions and properties are important for
17 ~~understanding and monitoring of a range of oceanographic phenomena. The characteristics and~~
18 ~~distributions of water masses in biogeochemical space are useful for, in particular, chemical and~~
19 ~~biological oceanography to understand the origin and mixing history of water samples. Here we define~~
20 ~~the characteristics of the major water masses in the Atlantic Ocean~~ as Source Water Types (SWTs) from
21 their formation areas, ~~and map out their distributions. The SWTs are described~~ by six key-properties
22 ~~based on taken from the biased adjusted data product~~ GLODAPv2-~~observational data. These include,~~
23 ~~including~~ both conservative (~~potential~~conservative temperature and ~~absolute~~ salinity) and non-
24 conservative (oxygen, silicate, phosphate and nitrate) ~~variables-properties. The distributions of these~~
25 ~~water masses are investigated with the use of the Optimal Multi-Parameter (OMP) method and mapped~~
26 ~~out.~~ The Atlantic Ocean is divided into four vertical layers by distinct ~~potential~~neutral densities ~~in the~~
27 ~~shallow and intermediate water column, and additionally by concentration of silicate in the deep~~
28 ~~waters and four zonal layers to guide the identification and characterization.~~ The water masses in the
29 upper layer ~~originate~~originate from ~~winter-time~~subduction ~~during winter~~ and are defined as ~~central~~
30 ~~waters, formed in four distinct areas: East North Atlantic Central water (ENACW), West North Atlantic~~
31 ~~Central Water (WNACW), East South Atlantic Central Water (ESACW) and West South Atlantic~~
32 ~~Central Water (WSACW)-Waters.~~ Below the upper layer, the intermediate layer consists of three main
33 water masses; Antarctic Intermediate Water (AAIW), Subarctic Intermediate Water (SAIW) and
34 Mediterranean ~~Overflow~~Water (MOWMW). The North Atlantic Deep Water (NADW, ~~divided into its~~
35 ~~upper and lower components~~) is the dominating water mass in the deep and overflow layer, ~~and is~~
36 ~~divided into upper and lower NADW based on the different origins and properties.~~ The origin of both
37 the upper and lower NADW is the Labrador Sea Water (LSW), the Iceland-Scotland Overflow Water
38 (ISOW) and ~~the~~Denmark Strait Overflow Water (DSOW). ~~The~~ Antarctic Bottom Water (AABW) is the
39 only natural water mass in the bottom layer and this water mass is redefined as North East Atlantic
40 Bottom Water (NEABW) in the north of equator due to the change of key properties, especial silicate.
41 Similar with NADW, two additional water masses, Circumpolar Deep Water (CDW) and Weddell Sea
42 Bottom Water (WSBW), are defined in the Weddell Sea region in order to understand the origin of
43 AABW. ~~The distributions of the main water masses are further investigated with the Optimal Multi-~~
44 ~~Parameter (OMP) method and mapped out with their core potential densities in the Atlantic Ocean. The~~
45 ~~mass conservation residual is inevitably larger than 100%, especially in the Central Waters, but it doesn't~~
46 ~~actually affect the determination to the distributions of water masses. The definitions of SWTs and~~
47 ~~distributions of water masses in biogeochemical space are useful for, in particular, chemical and~~
48 ~~biological oceanography to understand the origin and mixing history of water samples.~~

49 **Key Words:** Atlantic Ocean, Water Mass, Source Water Types, GLODAP, Optimal-Multi-Parameter
50 Analysis
51

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52 **1 Introduction**

53 ~~Properties of the water in the ocean are not uniformly distributed so that different regions and depths (or~~
54 ~~densities) have different characteristics. Bodies of water with similar properties often share a common~~
55 ~~formation history and are referred to as a water mass.~~ ~~The ocean is composed a large number of water~~
56 ~~masses that are not simply piled up on top of, or next to each other, like bricks. In fact, water masses~~
57 ~~have now~~ ~~without clear boundaries, instead there are but gradual transformation~~ ~~transformations~~ ~~between~~
58 ~~them~~ ~~each other, (e.g. Castro et al., 1998).~~ ~~Understanding of the distributions and variations of water~~
59 ~~masses play is important for~~ ~~Properties of the water in the ocean are not uniformly distributed and the~~
60 ~~characteristics vary with regions and depths (or densities). The water masses, which are defined as~~
61 ~~bodies of water with similar properties and common formation history, are referred to as a body of water~~
62 ~~with a measurable extent both in the vertical and horizontal, and thus a quantifiable volume (e.g.~~
63 ~~Helland-Hansen, 1916; Montgomery, 1958). Mixing occurs inevitably between water masses, both~~
64 ~~along and across density surfaces, and result in mixtures with different properties away from their~~
65 ~~formation areas. Understanding of the distributions and variations of water masses have significance to~~
66 ~~several disciplines of oceanography, for instance while investigating the thermohaline circulation of the~~
67 ~~world ocean or predicting climate change (e.g. Haine & Hall, 2002, Tomczak, 1999).~~ ~~Also important is~~
68 ~~the concepts~~ ~~(e.g. Haine and Hall, 2002; Tomczak and Godfrey, 2013; Morrison et al., 2015).~~

69 ~~The concept~~ ~~of water masses is also important for biogeochemical and biological applications, where~~
70 ~~the transformations of properties over time can be successfully viewed in the water masses frame-work.~~
71 ~~For instance, the formation of Denmark Strait Overflow Water in the Denmark Strait could be~~ ~~was~~
72 ~~described using mixing of a large number of water masses from the Arctic Ocean and the Nordic Seas~~
73 ~~(Tanhua et al., 2005).~~ ~~In a more recent work,~~ ~~Garcia-Ibanez et al. (2015), (Tanhua et al., 2005).~~ ~~Numbers~~
74 ~~of investigations show the significance of knowledge about water masses to the biogeochemical~~
75 ~~oceanography, for instance, the investigation of mineralization of biogenic materials (Alvarez et al.,~~
76 ~~2014) or the change of ventilation in the Oxygen Minimum Zone (Karstensen et al., 2008).~~ ~~In a more~~
77 ~~recent work, Garcia-Ibanez et al. (2015) considered 14 water masses combined with velocity fields to~~
78 ~~estimate transport of water mass, and thus chemical constituents, in the north Atlantic. Similarly, Jullion~~
79 ~~et al. (2017) used water mass analysis in the Mediterranean Sea to better understand the dynamics of~~
80 ~~dissolved Barium. However, the lack of a unified definition of overview water masses on an oceanic or~~
81 ~~even global scale leads to an additional and repetitive amount of work by redefining water masses in~~
82 ~~specific regions. The goal of this study is to facilitate water mass analysis in the Atlantic Ocean and in~~
83 ~~particularly we aim at supporting biogeochemical and biological oceanographic work in a broad sense,~~

84 ~~A water mass is a body of water that originates in a particular area of the ocean with a common formation~~
85 ~~history, in other words, seawater from one water mass shares common properties such as temperature,~~
86 ~~salinity and biogeochemical properties that are distinct from surrounding bodies of water (e.g.~~
87 ~~Montgomery, 1958, Helland-Hansen, 1916) and have a measurable extent both in the vertical and~~

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88 horizontal, and thus a quantifiable volume. Since each water mass is surrounded by other water masses,
89 mixing occurs inevitably between them both along and across density surfaces. As a result, mixtures of
90 water masses with different properties tend to be found away from their formation areas. Early work by
91 Jacobson (1927) and Defant (1929) clarified the application of T-S relationship in the oceanography,
92 and Wüst and Defant (1936) illustrated the stratification and circulation of water masses in the Atlantic
93 Ocean based on the observational data from Meteor Cruise 1925-1927. Since the first publication of
94 global distributions of water masses (Sverdrup, 1942), early studies on water masses are mainly based
95 on potential temperature (θ) and salinity (S). Emery and Meincke (1986) made a summary and review
96 on this kind of analysis. The limitation of this method is that distribution of more (more than three) water
97 masses cannot be calculated at the same time with only these two parameters. So during the same time
98 as the development of this theory, physical and chemical oceanographers also tried to add more
99 parameters to the calculation and the Optimum Multi-parameter (OMP) analysis is one of the typical
100 products (Poole & Tomczak, 1999). This concept of water masses has been redefined over time, and in
101 Emery and Meincke (1986) the water masses were divided into upper, intermediate and deep/abyssal
102 layers based on the depth and the T-S relationship. With the development of observational capacities for
103 a range of variables and the data base to evaluate them, definition of water masses is not limited to the
104 T-S-P relationship. Additional physical and chemical properties, both conservative and non-
105 conservative, are added to the water mass concept (e.g. Tomczak, 1981). These additional variables
106 exhibit different importance in defining different water masses, but are complementary to each other
107 and provide a more solid basis for water mass definitions. Based on research during last several decades,
108 Tomczak (1999) summarized the history of the water mass research and provided an outlook for the
109 evolution of water mass research. Tomczak (1981) extended the analysis into more than three water
110 masses by adding more parameters/water properties (such as phosphate and silicate) and solving the
111 equations of linear mixing without assumptions. In Tomczak and Large (1989), this method was
112 successfully applied to the analysis of mixing in the thermocline in Eastern Indian Ocean.

113 Accurate definition and characterization of water masses is the first step for performing any further
114 analysis, such as the Optimum Multi-parameter (OMP) analysis (Tomczak & Large, 1989). In this study,
115 the concepts and definitions of water masses as given by Tomczak (1999) are used and we aim at
116 defining the properties of the main water masses in the Atlantic Ocean, and to view the distribution of
117 the water masses. In order to facilitate the water mass analysis, the Atlantic data from the data product
118 GLODAPv2 (Lauvset et al., 2016) are used to identify and define the properties for the most prominent
119 water masses in the Atlantic Ocean based on 6 commonly measured physical and biogeochemical
120 variables (Figure 1). The goal of this work is to facilitate water mass analysis and in particularly we
121 aim at supporting biogeochemical and biological oceanographic work in a broad sense. The water
122 masses in this study are defined in a static sense, i.e. they are assumed to be steady and do not change
123 with time, and that our analysis is relatively coarse in that we do not consider subtle differences between
124 closely related water masses but rather paint the picture with a rather broad brush. Studies looking at

125 temporal variability of water masses, or water mass formation processes in detail, for instance, may find
126 this study useful but will certainly want to use a more granular approach to water mass analysis in their
127 particular area. The definitions of water masses are further used to estimate the distributions of the water
128 masses representative sections/cruises in the Atlantic Ocean based on the GLODAPv2 dataset.

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

134 Understanding the formation, transformation, and circulation of water masses has been a research topic
135 in oceanography since the 1920s (e.g. Jacobsen, 1927; Defant, 1929; Wüst and Defant, 1936; Sverdrup,
136 1942 etc.). The early studies were mainly based on (potential) temperature and (practical) salinity as
137 summarized by Emery and Meincke (1986). The limitation of the analysis based on T—S relationship
138 is obvious; distributions of more (than three) water masses cannot be analyzed at the same time with
139 only these two parameters, so physical and chemical oceanographers has worked to add more parameters
140 to the characterization of water masses (e.g. Tomczak and Large, 1989; Tomczak, 1981; 1999). The
141 Optimum Multi-parameter (OMP) method extends the analysis so that more water masses can be
142 considered by adding parameters/water properties (such as phosphate and silicate) and solving the
143 equations of linear mixing without assumptions. The OMP analysis has been successfully applied in a
144 range of studies, for instance for the analysis of mixing in the thermocline in Eastern Indian Ocean
145 (Poole and Tomczak, 1999).

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

158 **2 Data and Methods**

159 **2.1 The GLODAPv2 ~~dataset~~ data product**

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

171 ~~In this work we use the GLODAPv2 data product (Olsen et al., 2016)is used~~ to quantify the
172 characteristics of water masses, ~~since this product is~~. The data in the GLODAPv2 product has passed
173 both a primary quality control (QC), aiming at precision of the data and unify the units, and a secondary
174 data quality control, aiming at the accuracy of the data (~~Olsen et al., 2016; 2019~~). ~~The GLODAPv2 data~~
175 ~~product is thus adjusted to correct for any biases in data. Through these QC routines, the GLODAPv2~~
176 ~~product is unique in its internal consistency, and is thus an ideal product to use for this work aiming at~~
177 ~~definitions of major water masses and source water types in the Atlantic Ocean.(Tanhua et al., 2010).~~
178 ~~The GLODAPv2 data product is adjusted to correct for any biases in data through these QC routines~~
179 ~~and is unique in its internal consistency, and is thus an ideal product to use for this work aiming.~~ Armed
180 with the internally consistent data in GLODAPv2, we utilize previously published studies on water
181 masses and their formation areas to define areas and depth-/density ranges that can be considered to be
182 representative samples of a water masses.

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

189 2.2 Water Masses (WMs) and Source Water Types (SWTs)

190 ~~In practice, defining properties of water masses (WMs) is often a difficult and time-consuming part,~~
191 ~~particularly when analyzing data from water masses in a region distant from their formation areas. An~~
192 ~~excellent discussion of water masses is found in Tomczak (1999), and we refer to this work for a more~~
193 ~~in depth discussion. Tomczak (1999) defines “defined a water mass as “a body of water with a common~~
194 ~~formation history, having its origin and origins in a particular region of the ocean”. Tomczak (1999)~~
195 ~~continues: “Water masses are physical entities with a measurable volume and therefore occupy a finite~~

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196 volume in the ocean. In their formation region they have exclusive occupation of a particular part of the
197 ocean; elsewhere they share the ocean with other water masses with which they mix. The total volume
198 of a water mass is given by the sum of all its elements regardless of their location.”

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

217 2.3 OMP Analysis

218 2.3.1 Principle of OMP Analysis

219 For the analysis ~~in this study we used,~~ six key properties are used to define water masses. ~~Those~~
220 ~~include~~ SWTs, including two conservative ~~properties (potential (conservative temperature and absolute~~
221 ~~salinity) and four non-conservative (oxygen, silicate, phosphate and nitrate) properties~~ to define the
222 ~~water masses.~~ In order to determine the ~~distribution of water masses,~~ distributions of WMs, the OMP
223 ~~analysis is invoked as~~ objective mathematical formulations of the influence of mixing is used. ~~As a~~
224 ~~summary (Karstensen and practical use of Tomczak, 1997; 1998). The starting point is the above results,~~
225 ~~the OMP analysis was developed and successfully applied in the analysis of water masses in specific~~
226 ~~regions (e.g. Karstensen & Tomczak, 1998, Karstensen & Tomczak, 1997). Observed properties~~ 6 key
227 ~~properties (Figure 1) from a water sample are compared with~~ observational sampling (such as CT_{obs} is
228 ~~the observational conservative temperature). The OMP model determines the contributions from~~
229 ~~predefined SWTs (such as CT_i shows the properties of conservative temperature in each “pure” water~~
230 ~~masses to quantify~~ SWT), which represent the mix of water masses that constitutes a water sample. The
231 ~~theory and formulas in values of the OMP analysis are described in detail in Tomczak and Large (1989)~~

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232 and the website <http://omp.geomar.de/>. Here we make a brief introduction to the OMP calculation that
 233 relates directly to our research. OMP analysis is based on a simple model of “unmixed” WMs in
 234 formation areas, through a linear set of following mixing equations, assuming that all key properties of
 235 water masses are affected by the same mixing process, and then to determine the distribution and of
 236 water masses through the following linear equation processes. The fractions (x_i) in each sampling point
 237 are obtained by finding the best linear mixing combination in parameter space defined by 6 key
 238 properties and minimizing the residuals (R , such as R_{CT} is the residual of conservative temperature) in
 239 a nonnegative least squares sense (Lawson and Hanson, 1974) as shown in the following equations:

240 ~~$G \cdot x$~~ $x_1CT_1 + x_2CT_2 + \dots + x_nCT_n = CT_{obs} + R_{CT}$

241 $x_1SA_1 + x_2SA_2 + \dots + x_nSA_n = SA_{obs} + R_{SA}$

242 $x_1O_1 + x_2O_2 + \dots + x_nO_n = O_{obs} + R_O$

243 $x_1Si_1 + x_2Si_2 + \dots + x_nSi_n = Si_{obs} + R_{Si}$

244 $x_1Ph_1 + x_2Ph_2 + \dots + x_nPh_n = Ph_{obs} + R_{Ph}$

245 $x_1N_1 + x_2N_2 + \dots + x_nN_n = N_{obs} + R_N$

246 $x_1 + x_2 + \dots + x_n = 1 + R$

247 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 ,
 248 Si_i , Ph_i and N_i ($i = 1, 2 \dots, n$) represent the predetermined (known) values in each SWT for each property.
 249 The last row expresses the condition of mass conservation.

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

257 $G \cdot x - d = R;$

258 Where G is a parameter matrix of defined source water types (SWTs with 6 key properties in this study),
 259 x is a vector containing the relative contributions of from the “unmixed” water types masses to the sample
 260 (i.e. solution vector of the source water type SWT fractions), d is a data vector of water samples
 261 (observational data from GLODAPv2 in this study) and R is a vector of residual. The solution is to find
 262 out the minimum the residual (R) with linear fit of parameters (key properties) for each data point with

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263 a non-negative values. ~~In this study, the mixed layer is not considered as its properties tend to be strongly~~
264 ~~variable on seasonal time-scales so that water mass analysis is inapplicable.~~

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265 Prerequisites**2.3.2 Extended OMP Analysis**

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

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270 ~~However, the biogeochemical process cannot be ignored in a basin-scale analysis (Karstensen and~~
271 ~~Tomczak, 1998).~~ Obviously, this prerequisite does not apply to our investigation for the entire Atlantic
272 ~~scale, so we use the “extended” OMP; analysis is required.~~ In this concept, non-conservative parameters

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273 (phosphate and nitrate) are converted into conservative parameters by introducing the ~~“preformed”~~
274 nutrients PO and NO, where PO and NO ~~show~~ ~~denotes~~ the concentrations of phosphate and nitrate in
275 seawater by considering the consumption of dissolved oxygen from respiration (in other words, the
276 alteration due to respiration is eliminated) (Karstensen & Tomczak, 1998, Broecker, 1974). ~~In this study,~~

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277 ~~the mixed layer is not considered as its properties tend to be strongly variable on seasonal time scales~~
278 ~~so that water mass analysis is inapplicable.~~ (Broecker, 1974; Karstensen and Tomczak, 1998). In addition,
279 ~~a new column should be added to the equations for non-conservative properties (aΔO₂, aΔSi, aΔPh and~~
280 ~~aΔN) to express the changes in SWTs due to biogeochemical impacts, namely, the change of oxygen~~
281 ~~concentration with the remineralization of nutrients;~~

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

$$294 \cancel{x_1CT_1 + x_2CT_2 + \dots + x_nCT_n} = CT_{obs} + R_{CT}$$

$$295 \cancel{x_1SA_1 + x_2SA_2 + \dots + x_nSA_n} = SA_{obs} + R_{SA}$$

$$296 \cancel{x_1O_1 + x_2O_2 + \dots + x_nO_n} - a\Delta O_2 = O_{obs} + R_O$$

$$297 \cancel{x_1Si_1 + x_2Si_2 + \dots + x_nSi_n} + a\Delta Si = Si_{obs} + R_{Si}$$

$$x_1Ph_1 + x_2Ph_2 + \dots + x_nPh_n + a\Delta Ph = Ph_{obs} + R_{Ph}$$

$$x_1N_1 + x_2N_2 + \dots + x_nN_n + a\Delta N = N_{obs} + R_N$$

$$x_1 + x_2 + \dots + x_n = 1 + R$$

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 WMs 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.~~ However, 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- ($\gamma < 27.10 \text{ kg m}^{-3}$, Figure 2). The reason is that ~~the key properties, for instance CT, of Central Water itself is~~ 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-percent%, but the total fraction is more than 100-percent% when added together. In our analysis this study, the total fraction is mostly fractions are generally less than 105% ($\gamma > 27.10 \text{ kg m}^{-3}$, Figure 2).

In order to map the distributions of water masses, all GLODAPv2 data in the Atlantic Ocean (below ~~410%~~ 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 (γ at 26.70 and 27.30 kg m^{-3} , latitude of 30 °N, Table 1). In this way, we end up with a set of 17 different OMP formulations

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331 that are used for estimating the fraction(s) of water masses in each water sample. The neutral density
332 and the latitude of the water sample are thus used to determine which OMP should be applied (Table 1).
333 Note that all water masses are present in more than one OMP so that reasonable (i.e. few are more than
334 ±20%-smooth) transitions between the different areas can be realized.

335 3 Overview of the water masses in the Atlantic Ocean and the Criteria of Selection

336 In line with the results from Emery and Meincke (1986) and from our interpretation of the observational
337 data from GLODAPv2, the water masses in the Atlantic Ocean are considered to be distributed in four
338 main isopycnal (vertical) layers (Figure 3) separated by surfaces of equal (neutral) density. (Figure 4).
339 The Upper Layer is the upper (shallowest) layer with lowest potential/neutral density under consideration
340 and is located within upper ~500-1000m —1000 m of the water column (below the mixed layer, σ_θ and
341 $\gamma < 27.0010 \text{ kg/m}^3 \text{ m}^{-3}$). The Intermediate Layer intermediate layer is located between ~1000 to
342 1500/2000m (σ_θ and 2000 m (γ between 27.0010 and 27.7090 $\text{kg/m}^3 \text{ m}^{-3}$). The Deep/deep and
343 Overflow/overflow layer occupies the layer roughly between ~2000—4000m (σ_θ γ between 27.7090 and
344 27.8828.10 kg/m^3 , although the boundary between deep and bottom layer south of equator is silicate
345 concentration less than 80 $\mu\text{mol/kg}$ rather than potential density m^{-3}) whereas the Bottom Layer bottom
346 layer is the deepest layer below the deep layer and mostly located below ~4000 meters depth. m
347 ($\gamma > 28.10 \text{ kg m}^{-3}$).

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

358 For the water masses in the upper layer, i.e. the central waters, an additional step is necessary; to the
359 Central Waters, properties cover a “wide” range instead of a “narrow” point value due to their variations,
360 especially in temperature (CT) and salinity (SA). i.e. The Central Waters are labeled by two SWTs to
361 identify the upper and lower boundaries of properties (Karstensen and Tomczak, 1997; 1998). In order
362 to determine the distribution ranges of each parameter since these water masses occupy the thermocline
363 and typically cover a wide range for all properties. Here we follow the method developed by (Karstensen
364 and Tomczak, 1997; 1998). One parameter (for instance potential temperature) two SWTs, one property
365 is taken as a benchmark (neutral density in this investigation) and the relationships between other
366 parameters to the others are plotted to make a linear fit and finally to find out the ranges of all parameters

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367 ~~the two endpoints are selected as the criteria of selection. In our investigation, potential density is used~~
368 ~~as the benchmark (Figure 4) instead of potential temperature since density plays a more significant role~~
369 ~~in the vertical stratification. This way we define a range for the variable within each water mass. SWTs~~
370 ~~to label Central Waters (Figure 6).~~

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

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

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394 ~~In this section, the horizontal (map views) and vertical (sections) distributions of the main water masses~~
395 ~~are also displayed. On the maps of horizontal view, fractions of water masses are plotted at each station~~
396 ~~with the interpolated format at their core densities. In order to avoid large interpolation errors, a station~~
397 ~~is considered as without data and plotted as grey rather than colored dots if there is no data within ± 0.1~~
398 ~~kg/m³ from core density. To exemplify the vertical distribution of the water masses, sections from five~~
399 ~~selected WOCE/GO-SHIP cruises, which together provide a reasonable representation of the Atlantic~~
400 ~~Ocean, are displayed (Figure 2 right panel). The A16 section, covering the full north-south extend of the~~
401 ~~Atlantic Ocean (Expocodes: 33RO20130803 & 33RO20131223), shows the meridional overview of all~~
402 ~~the main water masses. The A03 (Expocode: 74AB20050501) and A10 (Expocode: 33RO20110906)~~

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403 sections displays the zonal distribution of the water masses in the North (A03) and South (A10) Atlantic
 404 separately. The A25 (Expocode: 06MM20060523) section is located at a relative higher latitude region
 405 compared to the A03 section and better represent the deep and overflow waters in particular. From this
 406 cruise, we focus on the investigation of LSW, ISOW and DSOW, with the purpose to show the origin
 407 of upper and lower NADW. The SR04 (Expocode: 06AQ20101128) is a section in the Antarctic region
 408 near Weddell Sea with certain significance to show the origin and formation of AABW. We also show
 409 a rough overview figure illustrating the main currents in that density layer, and with the main formation
 410 region of each water mass indicated as striped boxes.

411 **4 The Upper Layer, Central Waters**

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

419 Central Waters can be easily recognized by their linear T–S relationships (Pollard et al., 1996,
 420 Stramma & England, 1999) ~~(Pollard et al., 1996; Stramma and England, 1999)~~. In this study, the Upper
 421 ~~Layer~~ upper layer is defined to be located above the potential neutral density isoline of $27.010 \text{ kg m}^{-3} \text{ m}^{-3}$
 422 (below the mixed layer). The ~~formation~~ formations and ~~transport~~ transports of the Central ~~Water is~~ Waters
 423 are influenced by the currents in ~~this~~ the upper layer and finally ~~forms a form~~ relative distinct ~~body~~ bodies
 424 of water in both the horizontal and vertical ~~directions~~ (Figure 8). The concept of Mode Water is ~~a similar~~
 425 ~~definition in the Upper Layer but referred to as the sub-regions of Central Water, which describes the~~
 426 particularly uniform properties of seawater within the upper layer and more refers to the physical
 427 properties (~~e.g. such as: T–S relationship and potential vorticity~~, ~~so~~). In this study, the unified name
 428 “Central Water” ~~”~~, which more refers to the biogeochemical properties ~~(Cianca et al., 2009; Alvarez~~
 429 ~~et al., 2014)~~, is used ~~in our study~~, to avoid possible confusions ~~(Cianca et al., 2009, Alvarez et al., 2014)~~.

430 **4.1 Eastern North Atlantic Central Water (ENACW)**

431 The main upper layer water mass in the region east of the Mid Atlantic Ridge (MAR) is the East North
 432 Atlantic Central Water (ENACW, (Harvey, 1982). This water mass is formed during winter and is
 433 subducted in the seas west of Iberian Peninsular. One component of the Subpolar Mode Water (SPMW)
 434 is carried south and contributes to the properties of ENACW (McCartney & Talley, 1982). In Figure 5,
 435 the linear T–S distribution of ENACW can be clearly seen, consistent with Pollard et al. (1996) and the
 436 definition of ENACW₁₂ in Garcia Ibanez et al. (2015). In Garcia Ibanez et al. (2015), there is another
 437 definition ENACW₁₆, but water samples show a discrete distribution warmer than 16 °C by GLODAPv2

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438 data set in this region, so also samples with potential temperature below 16 °C are selected in this study.
439 As shown in Figure 5, ENACW dominates the upper 500m depth. The main character of ENACW is the
440 large potential temperature and salinity ranges and low nutrients (especially low in silicate). The work
441 of Pollard et al. (1996) constitutes the main theoretical basis of our analysis. The region limited by
442 latitudes between 39 and 48 °N and longitudes between 15 and 25 °E (east of Mid-Atlantic Ridge), is
443 consider as the formation area of ENACW. Based on the work of Pollard and Pu (1985), potential density,
444 $\sigma_{\theta} = 26.50 \text{ kg/m}^3$ as higher boundary and $\sigma_{\theta} = 27.30 \text{ kg/m}^3$ are selected as the lower boundary to define
445 ENACW.

446 **4.2 — Western North Atlantic Central Water (WNACW)**

447 Western North Atlantic Central Water (WNACW) is another water mass formed through winter
448 subduction (McCartney & Talley, 1982, Worthington, 1959). WNACW is formed at the southern flank
449 of the Gulf Stream (Klein & Hogg, 1996) and is in some literatures referred to as 18 ° water since a
450 potential temperature of around 18 °C is one significant feature of this water mass (Talley & Raymer,
451 1982). In general, seawater in the Northeast Atlantic has higher salinity than in the Northwest Atlantic
452 due to the stronger winter convection (Pollard & Pu, 1985) and input of MOW (Pollard et al., 1996,
453 Prieto et al., 2015). However, for the central waters, the situation is the opposite. WNACW has a
454 significantly higher salinity than ENACW by 0.9 PSU units. In this study, we follow McCartney and
455 Talley (1982) and consider the region 24–37°N, 50–70°W as the formation area and pressure less than
456 1000 m. By defining the depth of WNACW, water samples show a discrete T-S distribution with
457 potential densities lower than 26.30 or larger than 26.60 kg/m³. Besides the potential density constraint,
458 the constraint is added that concentrations of phosphate lower than 0.3 and silicate lower than 3 μmol
459 kg⁻¹. The properties of WNACW are shown in Figure 5. Besides the linear T-S relationship, a feature of
460 all central waters, another feature of this water mass is, as the alternative name suggests, a potential
461 temperature around 18 °C. This is the warmest of the four STWs in the Atlantic Ocean since it has the
462 lowest latitude of formation and is influenced by the high salinity Gulf Stream during formation. Low
463 nutrients, including silicate, phosphate and nitrate are other features compared to other central waters
464 that generally are low in nutrients compared to deeper water masses

465 **4.3** The main Central Water in the region east of the Mid-Atlantic-Ridge (MAR) is the East North
466 Atlantic Central Water (ENACW, Harvey, 1982). This water mass is formed in the inter-gyre region
467 during the winter subduction (Pollard and Pu, 1985). One component of the Subpolar Mode Water
468 (SPMW) is carried south and contributes to the properties of ENACW (McCartney and Talley, 1982).
469 The inter-gyre region limited by latitudes between 39 and 48 °N and longitudes between 20 and 35 °W
470 (Pollard et al., 1996) is considered as the formation area of ENACW (Figure 5). Neutral densities of
471 26.50 and 27.30 kg m⁻³ are selected as the upper and lower boundaries to define the SWT of ENACW
472 (Cianca et al., 2009; Prieto et al., 2015), which is also in contrast to Garcia-Ibanez et al. (2015) that used
473 potential temperature (θ) as the upper limit. The core of ENACW is located within the upper 500 m

474 depth (Figure 7, a) with the iconic linear T-S relationship (Figure 6, b) consistent with Pollard et al.
475 (1996). The main character of ENACW is the large ranges of temperature (CT) and salinity (SA) and
476 low nutrient concentrations, especially silicate (Figure 7, b).

477 **4.2 Western North Atlantic Central Water (WNACW)**

478 Western North Atlantic Central Water (WNACW) is another water mass formed through winter
479 subduction (Worthington, 1959; McCartney and Talley, 1982) with the formation area at the southern
480 flank of the Gulf Stream (Klein and Hogg, 1996). In some studies, this water mass is referred to as 18 °C
481 water since a potential/conservative temperature of around 18 °C is one symbolic feature (e.g. Talley
482 and Raymer, 1982; Klein and Hogg, 1996). In general, seawater in the Northeast Atlantic has higher
483 salinity than in the Northwest Atlantic due to the stronger winter convection (Pollard and Pu, 1985) and
484 input of MW (Pollard et al., 1996; Prieto et al., 2015). However, for the Central Waters, the situation is
485 the opposite. WNACW has a significantly higher salinity (SA) by ~0.9 g kg⁻¹ than ENACW (Table 4).
486 In this study, work from McCartney and Talley (1982) is followed and the region 24—37°N, 50—70°W
487 is considered as the formation area (Figure 5) with depth less than 500 m. By defining the SWT of
488 WNACW, neutral density between 26.20 and 26.70 kg m⁻³ is selected since the discrete T—S
489 distribution outside this range (Table 2). Besides the linear T—S relationship, another property of this
490 water mass is, as the alternative name suggests, a conservative temperature around 18 °C, which is the
491 warmest in the four Central Waters due to the lowest latitude of formation area and the impact from the
492 warm Gulf Stream (Cianca et al., 2009; Prieto et al., 2015). In addition, low nutrient is also a significant
493 property compared to other Central Waters (Figure 2 in Supplement).

494 **4.3 Eastern South Atlantic Central Water (ESACW)**

495 The formation area of ESACW is located in area southwest of South Africa and south of the Benguela
496 Current (Peterson and Stramma, 1991). In this region the Agulhas Current brings water from the Indian
497 Ocean (Deruijter, 1982; Lutjeharms and van Ballegooyen, 1988) that mixes with the South Atlantic
498 Current from the west (Stramma and Peterson, 1990; Gordon et al., 1992). The origin of ESACW can
499 partly be tracked back to the WSACW, but defined as a new SWT since seawater from Indian Ocean is
500 added by the Agulhas Current. The mixing region of Agulhas Current and South Atlantic Current (30—
501 40 °S, 0—20 °E) is selected as the formation area of ESACW (Figure 5). To investigate the properties
502 of ESACW, results from Stramma and England (1999) is followed and consider 200—700m as the core
503 of this water mass. For the properties, neutral density (γ) between 26.00 and 27.00 kg m⁻³ and oxygen
504 concentration higher than 230 μ mol kg⁻¹ are used to define ESACW (Table 2). Similar as ENACW,
505 ESACW also exhibits relative large CT and SA ranges and low nutrient concentrations (especially low
506 in silicate) compared to the AAIW below. The properties in ESACW are similar to that of WSACW,
507 although with higher nutrient concentrations due to input from the Agulhas current (Figure 3 in
508 Supplement).

509 **4.4 Western South Atlantic Central Water (WSACW)**

510 The WSACW is formed in the region near the South American coast between 30 and 45 °S, where
511 surface South Atlantic Current brings ~~central water~~Central Water to the east (Kuhlbrodt et al., 2007).
512 ~~The WSACW is formed with little directly influence from other central water masses~~ (Stramma &
513 England, 1999); ~~while the origin of other central water masses (e.g. ESACW or ENACW) can, to some~~
514 ~~extent at least, be traced back to WSACW~~ (Peterson & Stramma, 1991). ~~This water mass is a product~~
515 ~~of three mode waters~~The WSACW is formed with little directly influence from other Central Water
516 ~~mass~~ (Sprintall and Tomczak, 1993; Stramma and England, 1999), while the origin of other Central
517 ~~Waters (e.g. ESACW or ENACW) can be traced back, to some extent at least, to WSACW~~ (Peterson
518 ~~and Stramma, 1991). This water mass is a product of three Mode Waters mixed together: the Brazil~~
519 ~~current brings Salinity Maximum Water (SMW) and Subtropical Mode Water (STMW) from the north,~~
520 ~~while the Falkland Current brings~~ ~~Subarctic~~Subantarctic Mode Water (SAMW) from the south (~~Alvarez~~
521 ~~et al., 2014~~). Here we follow the work of Stramma and England (1999) and Alvarez et al. (2014) that
522 choose the meeting region of these two currents (25—60 °W, 30—45 °S) as the formation ~~region~~area
523 ~~of WSACW. We choose potential~~ (Figure 5). Neutral density (σ_{θ}) between 26.0 and 27.0 kg/m³ and
524 ~~salinity higher than 34.5 for defining~~ m⁻³ is selected to define the SWT of WSACW. ~~In addition to the~~
525 ~~physical properties we used and~~ the requirement of silicate concentrations lower than 405 $\mu\text{mol kg}^{-1}$ and
526 oxygen concentrations lower than 230 $\mu\text{mol kg}^{-1}$ ~~to define this SWT~~ is also added (Table 2). WSACW
527 shows the similar hydrochemical properties to other Central Waters such as linear T-S relationship with
528 large T and S ranges and low concentration of nutrients, especially silicate (Figure 4 in Supplement).

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

534 **4.4 Eastern South Atlantic Central Water (ESACW)**

535 The other formation area of SACW in the eastern South Atlantic Ocean is located in area southwest of
536 South Africa and spreads to the north along the Benguela Current (Peterson & Stramma, 1991). ~~In this~~
537 ~~region the Agulhas Current brings water from the Indian Ocean~~ (Deruijter, 1982, Lutjeharms & van
538 Ballegooyen, 1988) ~~that meets and mixes with the South Atlantic Current~~ (Gordon et al., 1992, Stramma
539 & Peterson, 1990) ~~from the west. Tracing back to the origin of ESACW, it can be considered as partly~~
540 ~~originating from WSACW, but since water from Indian Ocean is added by the Agulhas Current we can~~
541 ~~define WSACW as a new independent STW with characteristic properties.~~

542 ~~We choose the meeting region of Agulhas Current and South Atlantic Current (30-40 °S, 0-20 °E) as~~
543 ~~the formation area of ESACW and display properties of this SWT. To investigate the properties of~~

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544 ~~ESACW, we also follow Stramma and England (1999), and choose 200-700m as the core of this water~~
545 ~~mass. For the properties, potential density (σ_θ) between 26.00 and 27.20 kg/m³ and oxygen~~
546 ~~concentration between 200 and 240 $\mu\text{mol kg}^{-1}$ are used to define ESACW.~~

547 ~~Figure 5 clearly shows the linear T-S relationship for potential density (σ_θ) between 26.00 and 27.20 kg~~
548 ~~m³, which is consists with the general property of Central Waters (Harvey, 1982, Alvarez et al., 2014,~~
549 ~~Emery & Meincke, 1986). As shown in Figure 5, ESACW exhibits a relative large potential temperature~~
550 ~~and salinity range and low nutrient concentrations (especially low in silicate) compared to the AAIW~~
551 ~~below. The properties in ESACW are similar to that of WSACW, although with higher nutrient~~
552 ~~concentrations due to input from the Agulhas current.~~

553 **4.5 Atlantic Distribution of Central Waters**

554 Based on ~~our~~the OMP analysis on the GLODAPv2 data product ~~we can now describe~~, the physical
555 extent of the ~~central waters~~Central Waters can be described over the Atlantic Ocean. The horizontal
556 distributions of four ~~main water masses~~Central Waters in the ~~Upper Layer~~upper layer are shown on the
557 maps in Figure ~~6~~8 and the vertical ~~distribution~~distributions along selected GO-SHIP sections are found
558 in Figure ~~7~~9. In general, the eastern central waters, both ~~9~~Note that the northern and southern variations,
559 ~~have higher potential~~Central Waters are found at different densities, and ~~are thus found deeper,~~
560 ~~compared to western central waters. This can be seen well in Figure 7, where the difference in the eastern~~
561 ~~variations being denser, so that the there is significant overlap in the horizontal distribution. The vertical~~
562 ~~extent of the eastern vs. western central waters can be~~Central Waters is clearly seen in Figure ~~9~~9.

563 ~~The East North Atlantic Central Water (The ENACW)~~ is mainly found in the northeast part of North
564 Atlantic, near the formation area ~~west of in~~ the ~~Iberian Peninsula-inter-gyre region (Figure 8)~~. High
565 fractions of ENACW is also found in a band across the Atlantic at around 40°N, where the core of this
566 water mass is found at close to 1000 m depth in the western part of the basin, ~~(Figure 7-9)~~.

567 ~~The West North Atlantic Central Water (WNACW)~~ is predominantly found in the western basin of the
568 North Atlantic in ~~an east-west~~a zonal band between ~10°N and 40°N, ~~(Figure 6-8)~~. The vertical extent
569 of WNACW is significantly higher in the western basin with an extent of about 500 meter in the west,
570 tapering off towards the east, ~~(Figure 7-9)~~.

571 ~~The East South Atlantic Central Water (ESACW)~~ is found over most of the South Atlantic, as well as
572 in the tropical and subtropical north Atlantic, ~~(Figure 8)~~. The extent of ESACW do reach particular far
573 north in the eastern part of the basin where it is an important component over the Eastern Tropical North
574 Atlantic Oxygen Minimum Zone, roughly south of the Cape Verde Islands, ~~Figure 6-~~ In the vertical
575 direction, the ESACW is located below WSACW (Figure 9).

576 The horizontal distribution of ~~the West South Atlantic Central Water (WSACW) is similar to~~ does also
577 reach into the ~~ESACW, although~~northern hemisphere but is, obviously, concentrated in the western

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578 basin (Figure 8). In the vertical scale, the WSACW is not dominant in the South East Atlantic off Africa.
579 Although both central waters in the south Atlantic have similar horizontal extent, the WSACW
580 dominates also tends to dominate the upper layer of the South Atlantic, above the ESACW, (Figure 7.9).

581 **5 The Intermediate Layer**

582 The intermediate water masses have an origin in the upper 500m of the ocean and subduct into the
583 intermediate depth (1000–1500m) during their formation process. Similar to the upper layer Central
584 Waters, the distributions of the intermediate water masses Intermediate Waters are
585 significantly influenced by the major currents. (Figure 10, left). The potential neutral density (σ_{θ}) of
586 the intermediate water masses usually Intermediate Waters is in general between 27.0010 and 27.7090
587 kg m⁻³, which is our and selected as the definition of the intermediate layer Intermediate Layer.

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

595 **5.1 Antarctic Intermediate Water (AAIW)**

596 The Antarctic Intermediate Water (AAIW) is the main water mass in the intermediate depth of the South
597 Atlantic Ocean. This water mass originates from the surface layer north of the Antarctic Circumpolar
598 Current (ACC) in all three sectors of the Southern Ocean, in particular in the area east of the Drake
599 Passage in the Atlantic sector (McCartney, 1982, Alvarez et al., 2014). After formation, the AAIW
600 subducts and spreads northward along the continental slope of South America (Piola & Gordon, 1989).
601 The AAIW covers most of the Atlantic Ocean until ~40°N and the percentage shows a decrease trend
602 to the north (Kirchner et al., 2009). AAIW can be found through most of the Atlantic Ocean at the depth
603 between 500 and 1200m, below the layer of central water and above the deep waters (Talley, 1996). The
604 two main characteristic features of AAIW is low salinity and high oxygen concentration (Stramma &
605 England, 1999).

606 Based on the work by Stramma and England (1999), we choose the region between 55 and 40°S (east
607 of the Drake Passage) as the formation area of AAIW and look at depths below 200 m so that not only
608 AAIW samples in the formation area but also some samples during the subduction and spreading in the
609 primary stage are considered. As for the boundaries between AAIW and surrounding water masses,
610 including SACW in the north and NADW in the deep, there are several slightly different definitions. The
611 Antarctic Intermediate Water (AAIW) is the main Intermediate Water in the South Atlantic Ocean. This
612 water mass originates from the surface region north of the Antarctic Circumpolar Current (ACC) in all

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648 ~~only~~ the combination of these two end-members ~~when considering~~ ~~is considered in~~ the whole Atlantic
649 Ocean scale ~~study~~.

650 For ~~defining~~ the spatial boundaries we ~~follow~~ ~~followed~~ Arhan (1990) and ~~choose~~ ~~longitudes~~ ~~selected~~ the
651 ~~region~~ between 35 and 55 °W, and ~~latitudes between~~ 50 and 60 °N, i.e. the region along the Labrador
652 Current and north of the NAC as the formation area of SAIW (Figure 85). Within this area ~~we follow~~
653 ~~Read (2000), and choose~~ ~~potential, neutral~~ densities higher than 27.65 kg m⁻³ and ~~potential~~ ~~conservative~~
654 temperature higher than 4.5 °C ~~is selected~~ to define SAIW. ~~Similar to the definition of AAIW, we~~
655 ~~include samples by following~~ Read, (2000). Samples in the depth range from the MLD to ~~500m~~ 500 m
656 ~~are investigated~~ as the core layer of SAIW; ~~this pressure includes~~, which included the formation and
657 subduction of SAIW- (Table 2).

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

662 5.3— Mediterranean Overflow Water (MOW/MW)

663 The predecessor of the Mediterranean ~~Overflow~~ Water (MOW/MW) is ~~the~~ Mediterranean
664 ~~Waters~~ Overflow Water (MOW) flowing out through the Strait of Gibraltar, whose main component is
665 ~~the~~ modified Levantine Intermediate Water. This water mass is recognized by high salinity and
666 temperature and intermediate ~~potential~~ ~~neutral~~ density in the Northeast Atlantic Ocean (Carracedo et al.,
667 2016). After passing the Strait of Gibraltar, the ~~Mediterranean water mixes rapidly with the overlying~~
668 ~~ENACW leading to a sharp decrease of salinity and potential density~~ (Baringer & Price, 1997). ~~In Gulf~~
669 ~~of Cadiz, the outflow of MOW~~ MOW mixes rapidly with the overlying ENACW leading to a sharp
670 ~~decrease of salinity and forms the MW~~ (Baringer and Price, 1997). ~~In Gulf of Cadiz, the outflow of MW~~
671 turns into two branches: One branch continues to the west, descending the continental slope, mixing
672 with surrounding water masses in the intermediate depth and influence the water mass composition as
673 far west as the MAR (Price et al., 1993). The other branch spreads northwards along the coast of Iberian
674 ~~peninsula~~ Peninsula and along the European coast and its influence can be observed as far north as the
675 Norwegian Sea (Reid, 1979, Reid, 1978) ~~(Reid, 1978; 1979)~~. ~~The impact from MW is significant in~~
676 ~~almost the entire Northeast Atlantic in the Intermediate Layer (east of the MAR, Figure 7 in Supplement),~~
677 ~~with high conservative temperature and absolute salinity but low nutrients compared to other water~~
678 ~~masses~~.

679 Here we ~~follow~~ ~~followed~~ Baringer and Price (1997) and define MOW to be an independent water mass
680 represented by the high salinity (salinity between 36.35 and 36.65) samples with the formation area west
681 of the Strait of Gibraltar (Figure 8). The Mediterranean water is characterized by salinity higher than
682 38.4. Almost the entire Northeast Atlantic intermediate layer, east of the MAR, is influenced by MOW.
683 As the most characteristic property of MOW is the high salinity, we display a salinity section plot (Figure

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684 8) of A03 cruise from 2005 (74AB2005050), where the high salinity of MOW can be seen and how the
685 high salinity core erodes westward towards the MAR. The high potential temperature and salinity
686 compared to other water samples at same depth, and the characteristically low and nutrient
687 concentrations are evident in Figure 8. Due to the limited number of samples (less than 200) within our
688 definition of MOW in GLODAPv2, we refrain from showing the histogram. The properties of MOW
689 are shown in Figure 8 and Table 4. The SWT of MW by the high salinity (absolute salinity between 36.5
690 and 37.00 g kg⁻¹, Table 2) samples in the formation area west of the Strait of Gibraltar (Figure 5).

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691 **5.4 Atlantic Distributions of Intermediate Waters**

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692 A schematic of the main currents in the intermediate layer (σ_{θ} between 27.10 and 27.790 kg·m⁻³·m⁻³)
693 is shown in Figure 9 (left panel).

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

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

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716 The Antarctic Intermediate Water (AAIW) has a southern origin and is found at slightly lighter densities
717 (core potential density ~27.220 kg·m⁻³·m⁻³, Figure 10, right) compared to MOW and SAIW,
718 Figures 9 and 10. The AAIW is formed in the region south of 40°S where it sinks and spreads to

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719 the north at depth between ~1000 and 2000 m ~~at potential~~with neutral densities between 27.910 and
720 27.790 kg/m³. ~~In the South Atlantic, the~~ m³. The AAIW is the only Intermediate Layer water mass that
721 is formed in the southern hemisphere. Figure 9 shows the horizontal distribution of AAIW based on our
722 OMP analysis. ~~It dominate Intermediate Water in the South Atlantic and it is clear that the AAIW and~~
723 ~~dominate the intermediate layer in the South Atlantic with~~represents a lower contribution of this water
724 mass ~~going reduction of fractions during the pathway to the north; there is only minor contribution of~~
725 ~~with only AAIW north of the equator, or rather, a diluted version of the AAIW is~~part to be found in the
726 ~~tropical Atlantic; the equator and 30 °N (Figure 10 and Figure 11).~~

727 **6 — The Deep and Overflow Layer**

728 ~~To the deep and overflow water masses are found~~The Deep and Overflow Waters, located below the
729 ~~Intermediate Layer, intermediate layer, are~~intermediate layer, are approximately found from 4500~~2000~~ to 4000~~m~~, 4000 m with
730 ~~potential~~neutral densities between 27.7090 and 27.88~~28.10~~ kg/m³ m³. These water masses play a
731 ~~significant~~an indispensable role in the Atlantic Meridional Overturning Circulation (AMOC). The
732 source region of these waters is confined to the North Atlantic with their formation region either
733 ~~north~~south of the Greenland-Scotland ridge, or in the Labrador Sea. (Figure 5 and Figure 12, left). The
734 Denmark Strait Overflow Water (DSOW) and the Iceland-Scotland Overflow water (ISOW) originate
735 from Arctic Ocean and the Nordic Seas and ~~mainly enters~~enter the North Atlantic through ~~with~~either
736 the Denmark Strait of the Faroe Bank Channel. (Figure 12, left). In the North Atlantic, these two water
737 masses ~~sink~~descend, mainly following the topography. ~~These two water masses, meet and mix in the~~
738 Irminger Basin (Stramma et al., 2004, Tanhua et al., 2005)(Stramma et al., 2004; Tanhua et al., 2005),
739 and form the bulk of the lower North Atlantic Deep Water (INADW) (Read, 2000; Rhein et al.; 2011).
740 The Labrador Sea Water (LSW) is formed through winter deep convection in the Labrador and Irminger
741 Seas, and ~~make~~makes up the bulk of the upper North Atlantic Deep Water (uNADW). Due to intense
742 mixing processes ~~we define~~the LSW, DSOW and ISOW are defined as the water masses in north of
743 40 °N whereas south of this latitude ~~we consider~~the presence of the two variations of NADW: ~~are~~
744 considered (Figure 12, right).

745 ~~From the formation area~~In south of 40 °N, both variations of the NADW ~~spreads~~spread south mainly
746 with the Deep Western Boundary Current (DWBC, Figure 12, left) (Dengler et al., 2004) through the
747 Atlantic until ~50 °S where they meet ~~the~~ Antarctic Circumpolar Current (ACC). During the southward
748 transport, the NADW also spreads significantly in the zonal direction, ~~so that we can find NADW in the~~
749 ~~whole Atlantic basin at these densities~~ (Lozier, 2012), ~~so that the distribution of NADW covers mostly~~
750 ~~the whole Atlantic basin in the Deep and Overflow Layer (Figure 12, right).~~ The southward flow of
751 NADW ~~in the North Atlantic, is~~also an indispensable component of Atlantic Meridional Overturning
752 Circulation (AMOC) (Broecker & Denton, 1989, Elliot et al., 2002, Lynch-Stieglitz et al.,
753 2007). (Broecker and Denton, 1989; Elliot et al., 2002; Lynch-Stieglitz et al., 2007).

754 **6.1 — Labrador Sea Water (LSW)**

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755 As an important water mass ~~by its own virtue and for that contributes to~~ the formation of North Atlantic
 756 Deep Water (NADW), Labrador Sea Water (LSW) is predominant in mid-depth (between 1000m and
 757 2500m depth) in the Labrador Sea region (Elliot et al., 2002). ~~The LSW is formed in the region of~~
 758 ~~Labrador Sea by deep convection during winter~~ (Clarke & Gascard, 1983), ~~and is typically found at~~
 759 ~~mid depth with $\sigma_{\theta} = -27.77 \text{ kg/m}^3$. This water mass was noted by~~ (Wüst & Defant, 1936) ~~This water~~
 760 ~~mass was firstly noted by~~ (Wüst and Defant, 1936) due to its salinity minimum and later defined and
 761 named by Smith et al. (1937). ~~The LSW is formed by deep convection during the winter and is typically~~
 762 ~~found at depth with $\sigma_{\theta} = -27.77 \text{ kg m}^{-3}$ (Clarke and Gascard, 1983).~~ Since then the character has been
 763 identified as a contribution to the ~~driving mechanism of northward heat transport in the Atlantic~~
 764 ~~Meridional Overturning Circulation (AMOC)~~ (Rhein et al., 2011). The LSW is characterized by relative
 765 low salinity (lower than 34.9) and high oxygen concentration ($\sim 290 \text{ } \mu\text{mol/kg}$) (Talley & McCartney,
 766 1982). ~~Another important criterion of LSW is the potential density (σ_{θ}), that ranges from 27.68 to 27.88~~
 767 ~~kg/m^3 (Stramma et al., 2004, Kieke et al., 2006, Clarke & Gascard, 1983, Gascard & Clarke, 1983).~~ ~~In~~
 768 ~~the large spatial scale, LSW can be considered as one water mass~~ (Dickson & Brown, 1994), ~~however~~
 769 ~~significant differences of different "vintages" of LSW exist~~ (Kieke et al., 2006, Stramma et al., 2004).
 770 ~~LSW can broadly be kg^{-1} (Talley & McCartney, 1982).~~ Another important criterion of LSW is the
 771 ~~potential density (σ_{θ}), that ranges from 27.68 to 27.88 kg m^{-3} (Clarke and Gascard, 1983; Gascard and~~
 772 ~~Clarke, 1983; Stramma et al., 2004; Kieke et al., 2006).~~ In the large spatial scale, LSW can be considered
 773 ~~as one water mass~~ (Dickson and Brown, 1994), however significant differences of different "vintages"
 774 ~~of LSW exist~~ (Stramma et al., 2004; Kieke et al., 2006). In some references, this water mass is also
 775 ~~broadly~~ divided into upper Labrador Sea Water (uLSW) and classic Labrador Sea Water (cLSW) with
 776 the boundary between them at potential density of 27.74 kg m^{-3} (Smethie & Fine, 2001, Kieke et al.,
 777 2006, Kieke et al., 2007). ~~(Smethie and Fine, 2001, Kieke et al., 2006; 2007).~~ The LSW is considered as
 778 the main origin of the upper NADW (Talley & McCartney, 1982, Elliot et al., 2002). ~~(Talley and~~
 779 ~~Mccartney, 1982; Elliot et al., 2002).~~
 780 ~~In our analysis we consider~~ On the basis of the above work, the formation area of LSW is selected to
 781 include the Labrador Sea and Irminger Basin west of Mid Atlantic Ridge. For the purpose of our
 782 analysis (the whole scale of the Atlantic Ocean) we consider LSW as one integral water mass. Although
 783 the region between Labrador Sea is located in North Atlantic between the Labrador Peninsula Peninsular
 784 and Greenland, for this analysis we consider the formation region of LSW to include and parts of the
 785 Irminger Basin (Figure 11). Within this geographical region we follow the definition from 5). The neutral
 786 density (γ) between 27.70 to 28.10 kg m^{-3} as well as low conservative temperature ($\text{CT} < 4^{\circ}\text{C}$) are used
 787 to define SWT of LSW (Table 2) by considering Clarke and Gascard (1983) and Stramma and England
 788 (1999), defining LSW as samples with potential density (σ_{θ}) between 27.68 to 27.88 kg/m^3 (Figure 11)
 789 ~~in~~ with the depth range of 500-2000m (Elliot et al., 2002).

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790 ~~Trademark characteristics of LSW are relative low salinity and high oxygen concentration. Figure 11~~
791 ~~shows the histogram of all samples that we consider to represent LSW in this analysis.~~ The relatively
792 large spread in properties is indicative of the different “vintages” of LSW, in particular the bi-modal
793 distribution of density, and partly for oxygen- (Figure 8 in Supplement).

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794 **6.2 — Iceland-Scotland Overflow Water (ISOW)**

795 ~~The Iceland Scotland Overflow Water (ISOW) flows close to the bottom from the Iceland Sea to the~~
796 ~~North Atlantic in the region east of Iceland, mainly through the Faroe-Bank Channel (Swift, 1984; Lacan~~
797 ~~et al., 2004; Zou et al., 2020). ISOW turn into two main branches when passing the Charlie-Gibbs~~
798 ~~Fracture Zone (CGFZ), with the first one flowing through the Mid-Atlantic-Ridge, into the Irminger~~
799 ~~basin, where it meets and mixes with DSOW (Figure 12). The other branch is transported southward~~
800 ~~and mixes with Northeast Atlantic Bottom Water (NEABW) (Garcia-Ibanez et al., 2015). The pathway~~
801 ~~of ISOW closely follows the Mid-Atlantic-Ridge in the Iceland Basin and is characterized by high~~
802 ~~nutrient and low oxygen concentration. The following criteria, conservative temperature between 2.2~~
803 ~~and 3.3 °C and absolute salinity higher than 34.95 g kg⁻¹, are used to define the SWT of ISWO, and~~
804 ~~neutral density higher than 28.00 kg m⁻³ is added order to distinguish ISOW from LSW in the region~~
805 ~~west of MAR (Table 2 and Figure 9 in Supplement).~~

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806 **6.3 Denmark Strait Overflow Water (DSOW)**

807 ~~A number of water masses from the Arctic Ocean and the Nordic Seas flows through Denmark Strait~~
808 ~~west of Iceland. At the sill of the Denmark Strait and during the descent into the Irminger Sea, these~~
809 ~~water masses undergo intense mixing. This overflow water mass is considered as the coldest and densest~~
810 ~~component of the sea water in the Northwest Atlantic Ocean and constitute a significant part of the~~
811 ~~southward flowing NADW (Swift, 1980). Here we use samples from the Irminger Sea with potential~~
812 ~~density higher than 27.88 kg m⁻³ (Tanhua et al., 2005) for our definition of DSOW. In addition, we~~
813 ~~require the silicate concentration to be lower than 11 μmol/kg to distinguish DSOW from NEABW,~~
814 ~~which has a high silicate concentration. As shown in Figure 11, Samples from the Irminger Sea (Figure~~
815 ~~5) with neutral density higher than 28.15 kg m⁻³ (Table 2 and Figure 10 in Supplement) are used for the~~
816 ~~definition of DSOW (Rudels et al., 2002; Tanhua et al., 2005). DSOW is mostly found close to the bottom~~
817 ~~as expected for an overflow water. In addition to the high density and low temperature, DSOW also has~~
818 ~~high oxygen concentration (~ 290-310 μmol/kg).~~

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819 **6.3 — Iceland-Scotland Overflow Water (ISOW)**

820 ~~The Iceland-Scotland Overflow Water, ISOW, flows close to the bottom from the Iceland Sea to the~~
821 ~~North Atlantic in the region east of Iceland, mainly through the Faroe Bank Channel (Swift, 1984, Kissel~~
822 ~~et al., 1997). ISOW turn into two main branches when passing the Charlie-Gibbs Fracture Zone (CGFZ),~~
823 ~~with the first one flowing through the Mid-Atlantic Ridge, into the Irminger basin, where it meets and~~
824 ~~mixes with DSOW. The other branch is transported southward and mixes with Northeast Atlantic~~

825 ~~Bottom Water (NEABW) (Garcia Ibanez et al., 2015). The pathway of ISOW closely follows the Mid-~~
826 ~~Atlantic Ridge in the Iceland Basin and is characterized by high nutrient and low oxygen concentration.~~
827 ~~In order to safely distinguish ISOW from LSW in the region west of MAR, we define ISOW as samples~~
828 ~~with salinity higher than 34.95, potential density higher than 27.83 kg/m³. Figure 11 displays our~~
829 ~~characterization of ISOW in the Iceland Basin, which is consistent from the result in the literature~~
830 ~~(Garcia Ibanez et al., 2015).~~

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831 6.4 — Upper North Atlantic Deep Water (uNADW)

832 ~~The uNADW is mainly formed by mixing of ISOW and LSW, and we consider this to be considered as~~
833 ~~a distinct water mass just south of the Labrador Sea as this region is identified as the redefining area of~~
834 ~~upper and lower NADW (Dickson & Brown, 1994). We select the (Dickson and Brown, 1994). The~~
835 ~~region between latitude 40 and 50 °N, west of the MAR is selected as the formation/redefining area of~~
836 ~~NADW (Figure 12) and use the criteria of potential/neutral density between 27.72 and 27.82 kg/m³ 85~~
837 ~~and 28.05 kg m⁻³ and conservative temperature lower than 4.0 °C, with depth range from 1200 to~~
838 ~~2000m/2000 m (Table 2 and Figure 11 in Supplement) are used to define the SWT of uNADW (Stramma~~
839 ~~et al., 2004). As a product of mixing/mixture from LSW and ISOW, the uNADW obviously inherits~~
840 ~~many properties from LSW, but is also significantly influenced by the ISOW. The relative high~~
841 ~~temperature (~3.3 °C) is a significant feature of the uNADW together with relatively low oxygen (~280~~
842 ~~µmol kg⁻¹) and high nutrient concentrations, which is a universal symbol of deep water (Table 4).~~

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843 6.5 — Lower North Atlantic Deep Water (lNADW)

844 ~~We use the/The same geographic region to define-is selected as the as we did for the formation area of~~
845 ~~lNADW (Figure 5).uNADW. In this region, the ISOW and DSOW (with some influence of, influenced~~
846 ~~by LSW) will mix with each other and form the lower portion of NADW (Stramma et al., 2004). Water~~
847 ~~samples between depths of 2000 and 3000 m with potential/CT higher than ~2.5°C and neutral densities~~
848 ~~between 27.7695 and 27.8828.10 kg m⁻³ are selected to define the lNADW. From the data shown in~~
849 ~~Figure 12, lower NADW can be found with properties more similar to ISOW compared with DSOW.~~
850 ~~For instance, the values of salinity and oxygen concentration are closer to ISOW. For nutrients, the SWT~~
851 ~~of lNADW have almost the same values to ISOW, but the relatively high potential temperature shows~~
852 ~~that the impact from LSW.(Table 2 and Figure 12 in Supplement).~~

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853 6.6 — Atlantic Distributions of Deep and Overflow Waters

854 The water masses dominate the neutral density interval 27.7–27.8890–28.10 kg/m³ m⁻³ in the Atlantic
855 Ocean, Figure 13. In the area north of roughly 40 °N the overflow waters dominate the deeper layers as
856 well, except in the eastern basin where a significant contribution from the North East Atlantic Bottom
857 Water (NEABW, section 7). Due to our definition of the water masses, three water masses dominate the
858 region north of 40 °N in Figure 13: are Labrador Sea Water (LSW), Iceland-Scotland Overflow Water
859 (ISOW) and Denmark Strait Overflow Water (DSOW). In the region south from/of 40 °N the upper and

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860 lower NADW, considered as products from these three original overflow water masses, dominate-the
861 deep and overflow layer (Figure 12).

862 The Labrador Sea Water (LSW) is commonly characterized as two variations, “upper” and
863 “classic” although in this study we see consider this as one water mass-see in the discussion
864 above. Our analysis indicates that the LSW dominated dominates the North West Atlantic Ocean in the
865 characteristic density range. In Figure 1412, we choose to display they $\sigma_{\theta} = 27.74 - \sigma_{\theta} 95$ that corresponds
866 to the lighter version main property of the LSW- (Kieke et al., 2006; 2007). The LSW spreads east and
867 southward in the North Atlantic Ocean, but is less dominant in the area west of the Iberian Peninsula
868 where the presence of MOWMW from the Gulf of Cadiz tends to dominate that density level. Note that
869 although the LSW is slightly denser than the MOWMW, their density ranges do overlap- (Figure 12 and
870 13).

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

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875 The Denmark Strait Overflow Water (DSOW) is mainly found in the Irminger and Labrador Seas as the
876 densest layer close to the bottom- (Figure 11). Our analysis indicates a weak contribution of DSOW also
877 east of the MAR. South of the Grand Banks the DSOW is already significantly diluted and only low to
878 moderate fractions are found. Here we consider two new water masses, upper and lower NADW in the
879 region south of 40 °N. After passing 40 °N, upper and lower NADW, considered as independent water
880 masses- (Figure 12 and 13).

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881 The After passing 40 °N, the upper and lower North Atlantic Deep Water (u4 NADW) are considered
882 as independent water masses and dominate the most of the Atlantic Ocean in this density layer. The map
883 in Figure 1312 shows that upper NADW covers the most area, while the NADW lower NADW
884 is found mainly found in the west region near the Deep Western Boundary Current (DWBC), especially
885 in South Atlantic. In the vertical view based on sections (Figure 1514), the southward transports of both
886 upper and lower NADW can be seen until ~ 50 °S where they meets AABW in the ACC region. ▲

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887 7— The Bottom Layer and the Southern water masses

888 We define the bottom waters The Bottom Waters are defined as the densest water masses that occupy
889 the lowest layers of the water column, typically below 4000 m depth and with potential neutral densities
890 higher than 27.8828.10 kg/m^3 or a silicate concentration in excess of 80 $\mu\text{mol kg}^{-1} \text{ m}^{-3}$. These water
891 masses have an origin in the Southern Ocean (Figure 1615, left) and are also characterized by their high
892 silicate concentration-concentrations. The Antarctic Bottom Water (AABW) is the main water mass in
893 the bottom layer, and Bottom Layer (Figure 15, right). This water mass is formed in the Weddell Sea
894 region, south of Antarctic Circumpolar Current (ACC) through mixing of Circumpolar Deep Water

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929 Northeast Atlantic Bottom Water (NEABW), also called lower Northeast Atlantic Deep Water
930 (~~(NEADW in Garcia Ibanez et al. (2015))~~), (~~(NEADW, Garcia-Ibanez et al., 2015)~~), is mainly found below
931 4000m depth in the eastern basin of the North Atlantic. (~~Figure 5~~). This water mass is an extension of
932 AABW during the way to the north, since the ~~characteristics~~properties of AABW ~~changes~~change
933 significantly on the slow transport north ~~we choose to define. A new SWT is redefined for this as a new~~
934 ~~water mass in~~ north of the Equator, similar ~~to~~as the ~~formation~~redefinition of NADW south of the
935 Labrador Sea.

936 The region ~~following region~~, east of the MAR and between the equator and 30 °N, i.e. before NEABW
937 enters the Iberian Basin, is selected as the redefining area of NEABW (~~Figure 16~~). ~~We also use the. The~~
938 criteria of ~~water samples from a depth deeper than 4000m~~4000 m and ~~potential temperature~~CT, above
939 1.8 °C; ~~are also used (Table 2)~~. In the T—S diagram of NEABW (~~Figure 16~~) we can see the linear T-S
940 ~~relationship in Figure 3~~, similar ~~to~~T—S distribution between NEABW and AABW in the Weddell
941 ~~Sea can be seen~~ but with significantly higher potential temperatures and salinities, roughly CT and SA
942 of ~1.95 °C and 34.887, respectively, ~35.060 g kg⁻¹. Most NEABW samples have a ~~potential~~neutral
943 density higher than 27.8828.10 kg/m³ m⁻³ and NEABW is characterized by low ~~potential temperature~~
944 (θ), low salinityCT and SA, but high silicate concentration: (~~Figure 14 in Supplement~~). This
945 ~~shows~~further suggests that NEABW originates from AABW, although most properties have been
946 changed significantly from the ~~origin in the~~ South Atlantic.

947 7.3. Circumpolar Deep Water (CDW) / ~~Warm Deep Water (WDW)~~

948 Circumpolar Deep Water (CDW) ~~or, as it is also called, Warm Deep Water (WDW)~~, which has
949 significance to the thermohaline circulation during the wind-driven upwelling in the Southern Ocean
950 (~~Morrison et al., 2015~~), is the lighter of the two water masses ~~that constitutes~~contribute to AABW. ~~In~~
951 ~~our study, we consider~~ formation. The production of this water mass ~~that mixes with WSBW directly~~
952 ~~as CDW (WDW in van Heuven et al. (2011))~~. CDW is a product from ~~can be tracked to the southward~~
953 ~~flow of NADW and the large-scale mixing of several water masses~~ in the Antarctic Circumpolar Current
954 (ACC) region (van Heuven et al. 2011). ~~The production of CDW can be tracked to the southward flow~~
955 ~~of NADW:., 2011~~. At about 50°S, NADW is deflected upward by AABW before reaching the ACC;
956 (~~Figure 14, upper panel~~), this part of NADW ~~mixes with other water masses in the ACC and forms a~~
957 ~~new water mass~~. Then this water mass ~~spreads further southward and passes the ACC~~. We define CDW
958 ~~as a new water mass~~ into the ACC region, where it contacts with other water masses, including AAIW
959 ~~above and AABW below~~. After passing the ACC region, CDW splits into two branches at ~60 °S. The
960 ~~upper branch is upwelled and partly joint into the AAIW, while the rest spreads towards the coastal~~
961 ~~region, mixes with the cold fresh shelf water, sinks to the bottom and finally forms the Weddell Sea~~
962 ~~Bottom Water (WSBW), which is another contribution to the AABW (Marshall and Speer, 2012;~~
963 ~~Abernathey et al., 2016)~~. The lower branch sinks and mixes with the WSBW below and contributes to
964 ~~the formation of AABW~~.

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965 In this study, the SWTs of CDW is defined by considering the water samples south of ACC, lower branch
966 and the region between 55 and 65 °S is selected as the defining formation area.

967 (Figure 5). To specify define SWT of CDW we (lower branch), water samples are selected water samples
968 with from depth between 200 and 1000m in the this region east of 60°W between 55 and 65°S as the
969 core of CDW. We also placed the additional constraints of having salinity lower than 34.64 and potential
970 density are σ_t higher than 27.80 kg/m³. The properties of CDW are shown in Figure 17, 34.82 g kg⁻¹ and
971 CT between -0.5 and 1.0 °C (Table 2). Similar to other bottom/southern SWTs, CDW is
972 characterized also defined by high nutrient concentrations ((silicate, phosphate and nitrate) and low
973 oxygen concentration. The potential temperature of CDW is between 0 and 1 °C while the potential
974 density is larger than 27.8 kg/m³, and the salinity higher than 34.63 concentrations (Figure 15 in
975 Supplement).

976 7.4 Weddell Sea Bottom Water (WSBW)

977 The Weddell Sea Bottom Water (WSBW) is the densest water mass that takes part in the formation of
978 AABW. Similar to CDW, WSBW is also formed bottom layer. As mentioned in the Weddell Sea region,
979 relative warm water ($\sigma_t > 0$ °C) flows southward and above section, part of CDW from the upper branch
980 cools down to σ_t lower than -1 °C rapidly, by mixing with extremely cold shelf water that is transported
981 and sinks down to the bottom along the continental slope. WSBW is thus (Gordon, 2001). WSBW is
982 formed in the Weddell Sea basin below the depth of 3000m, before it meets and mixes with CDW/AABW.
983 Compared with CDW, its low potential. The low temperature of WSBW compared to CDW (CT = ~ -
984 0.8 °C) is a significant characteristic property of WSBW (van Heuven et al., 2011)(Figure 16 in
985 Supplement, van Heuven et al., 2011).

986 We follow van Heuven et al. (2011) and choose water samples in the latitudinal boundaries of 55 - 65 °S
987 in the Weddell Sea with pressures larger than 3000 m as the formation core area. We additionally
988 constrain our selection to samples with potential temperature lower than -0.7 °C and silicate higher than
989 105 μmol/kg. The properties of WSBW are shown in Figures 17. In addition to the physical properties,
990 such as low potential temperature and high potential density, WSBW has high nutrient concentrations,
991 but dislike CDW. Water samples in the latitudinal boundaries of 55 - 65 °S in the Weddell Sea (Figure
992 5) with pressures larger than 3000 m and CT lower than -0.7 °C and silicate higher than 105 μmol kg⁻¹
993 are selected to define the SWT of WSBW (Table 2), following Gordon (2001) and van Heuven et al.
994 (2011).

995 WSBW has high oxygen concentration.

996 7.5 Atlantic Distribution of the bottom waters and southern water masses

997 AABW and NEABW dominate the bottom layer ($\sigma_t > 27.88$ & $\gamma > 28.10$ kg/m³ m⁻³). From the aerial view
998 of the map horizontal distribution (Figure 18, 15) it can be seen that AABW and NEABW cover the
999 most bottom area of South and North Atlantic respectively. In fact, both water masses have the same

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1000 origin but ~~are~~ distinguished by ~~defining/redefining~~ a new SWT ~~as NEABW~~ due to the sharp reduction of
1001 silicate, ~~which is an important signal to label bottom water masses~~, after passing the equator (Figure
1002 ~~4916~~). The AABW is formed in the Weddell Sea region south of the Antarctic Circumpolar Current
1003 (ACC). After leaving the formation area, AABW ~~meets NADW and they have some~~ ~~suffers from~~ water
1004 exchange ~~from with NADW between 50 °S until and AABW reaches~~ the equator (van Heuven et al.,
1005 2011). ~~Similar to AABW, NEABW also mainly mixed with lower NADW between equator and 40 °N.~~
1006 ~~North of 40 °N, NEABW meets lower NADW with origins from ISOW (Garcia Ibanez et al.,~~
1007 ~~2015). Similar to AABW, NEABW also mainly contacts with lower NADW and its origin (ISOW) in the~~
1008 ~~North Atlantic (Garcia-Ibanez et al., 2015).~~

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1010 In the Weddell Sea ~~Region, where the AABW is formed, region~~, distributions of ~~two initial water masses,~~
1011 ~~CDW and WSBW are~~ ~~masse~~ mainly reflect the formation process of AABW as displayed based on SR04
1012 sections (Figure ~~2017~~). In the zonal section ~~across the Weddell Sea~~, AABW can be seen as the mixture
1013 of CDW and WSBW. ~~The, where the~~ core of CDW distributes in the upper 1000m and WSBW origins
1014 ~~at from~~ the surface and ~~subducts/sinks~~ along the continental slope into the bottom below 4000m. ~~This~~
1015 ~~result is consistent with (van Heuven et al., 2011).~~ Both original water masses meet each other at depth
1016 between ~2000 and 4000m, where AABW is formed, with main core locates at ~3000m. The meridional
1017 section shows the northward outflow of AABW into the Atlantic Ocean. AABW is located between
1018 2000 and 4000m, as a product from CDW and WSBW. After leaving Weddell Sea region, AABW is
1019 considered as an independent water mass and spreads further northward as the only bottom water mass
1020 until the equator.

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1021 ~~9~~

1022 **8. Conclusions and Discussion**

1023 ~~The~~ characteristics of the main water masses in their formation areas are defined in a ~~76~~-dimensional
1024 hydro-chemical space in the Atlantic Ocean. The values of properties for these water masses ~~forms form~~
1025 the fundamental basis to investigate ~~the their~~ transport, distribution and mixing ~~of water masses and~~
1026 ~~referred to as SWTs,~~ Table 4 ~~and Figure 3~~ provides an overview ~~of the properties, and the standard~~
1027 ~~deviation, SWTs~~ of all the 16 Atlantic Ocean ~~main~~ water masses considered in this study. ~~Seven often~~
1028 ~~measured hydro-chemical and physical variables~~ ~~The distribution of water masses are used to~~
1029 ~~characterize these main SWTs in the Atlantic Ocean. To guide the water masses descriptions, their~~
1030 ~~distributions are~~ estimated by using OMP analysis based on the GLODAPv2 data product, and
1031 ~~preliminarily~~ divided into four ~~main~~ vertical layers ~~roughly separated by potential density in the shallow~~
1032 ~~and concentration of silicate in the deep southern Hemisphere.~~ based on neutral densities,

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1033 The upper layer, which covers the most shallow layer (typically down to about 500 m depth) of the
1034 ocean below the mixed layer (the mixed layer is not consider in this analysis), is occupied by ~~central~~
1035 ~~waters~~. ~~Central Waters~~, The intermediate layer is situated between the upper layer and the deep ~~and~~
1036 ~~overflow~~ layer at roughly 1000 to 2000m depth. Of the three water masses in this layer, AAIW and
1037 SAIW are both characterized by relative low (~~absolute~~) salinity and (~~conservative~~) temperature, while
1038 the ~~MOW have~~ ~~MW contains~~ high ~~SSA~~ and ~~T-CT~~. ~~The SAIW and MOW are the two main water masses~~
1039 ~~commonly found~~ ~~MW show a Northwest-Southeast distribution~~ in the North Atlantic. ~~In~~, while the
1040 ~~AAIW dominates~~ the eastern part, ~~MOW overflows from the Mediterranean Sea, across the Strait of~~
1041 ~~Gibraltar and spreads to the north and west. In the South Atlantic, AAIW is the dominate water mass in~~
1042 ~~this layer. After the formation in the shallow layer, AAIW sinks into~~ intermediate depth (around 1000m)
1043 ~~and spreads to the north until~~ ~~20~~ layer of the region south of 30°N and this water mass can easily be
1044 ~~recognized with low salinity~~. In the deep and overflow layer between roughly 2000 and 4000m, ~~water~~
1045 ~~masses are found with an origin in the north Atlantic. NADW is the dominate water mass with~~ ~~NADW,~~
1046 ~~which contains~~ upper and lower portions, is recognized as the dominate water mass with a relative
1047 ~~complex origin from LSW, ISOW and DSOW~~. The bottom layer is occupied by ~~water masses~~ ~~AABW~~
1048 with a southern origin, ~~defined~~ ~~formed~~ by low potential temperatures, high densities and ~~CDW and~~
1049 ~~WSBW~~. After passing the equator, this water mass is redefined as NEABW due to the changes in
1050 ~~properties (silicate concentrations)~~.

1051 Besides the 16 main Atlantic Ocean water masses, additional water masses still exist and can be found
1052 in the Atlantic that cannot be explained by the mixing of any above listed original water masses. This
1053 tends to happen close to the coast by local oceanographic events, such water masses are not listed and
1054 considered as main water mass in this study and also no additional SWTs are defined. For instance, in
1055 the coastal region of Southern Benguela Upwelling System (15 – 20 °E, 30 – 34 °S), water samples are
1056 found with low temperature and oxygen (CT = ~8 °C, oxygen = ~150 μmol kg⁻¹). This cannot be
1057 explained by the mixing of ESACW and WSACW, which are the only two possible water masses in this
1058 region and depth, because the CT and oxygen of both water masses are higher than these values. One
1059 possible explanation is that low-oxygen water is carried by the upwelling from the lower (Flynn et al.,
1060 2020).

1061 The here presented characteristics (property ~~value~~ ~~values~~ and the standard ~~deviation~~ ~~deviations~~) of
1062 Atlantic Ocean water masses and ~~their distributions of water masses~~ are intended to guide water mass
1063 analysis of hydrographic data and expect to provide a basis for further biogeochemical research.

1066 Acknowledgements

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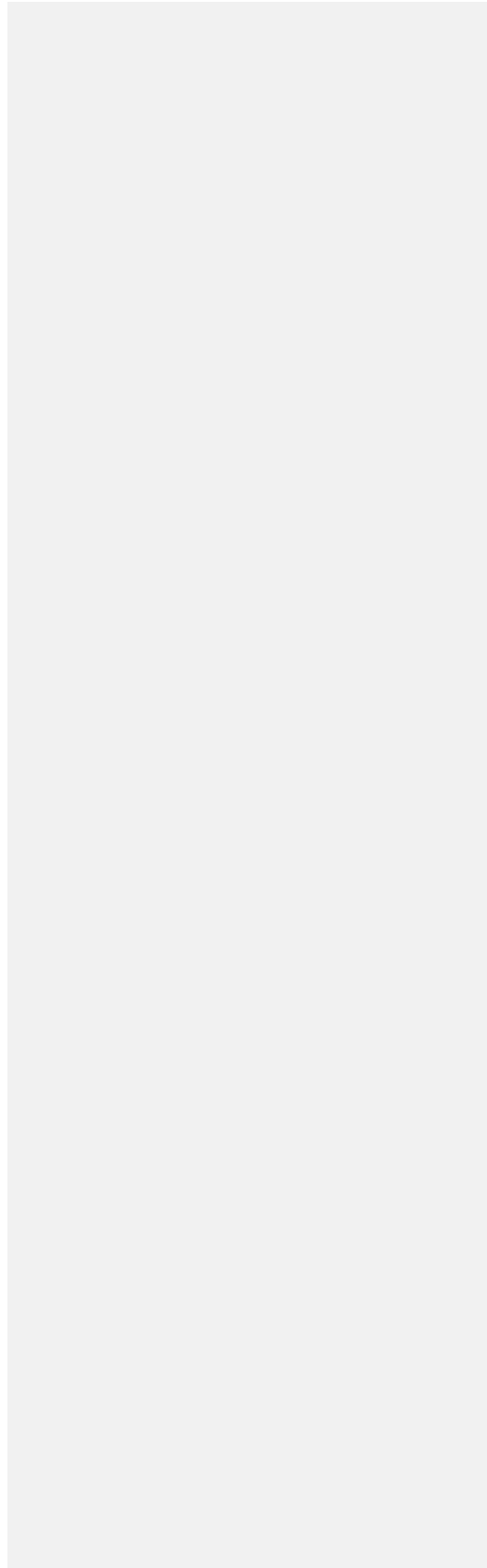
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