RC1: 'Comment on egusphere-2023-136', Anonymous Referee #1, 20 Mar 2023
Consistent picture of the horizontal circulation of the Atlantic Ocean over three decades

Cainzos et al

This is a detailed study of inverse model calculations of the major current systems (upper, intermediate and deep) throughout the Atlantic basin using 3 decades of hydrographic data of latitudinal sections from 45S up to 58N. Extensive comparisons of the results against past literature studies is presented. The final conclusion is that, at least from these data, there is no evidence of statistically significant changes in the current systems between decades. A nice set of figures are presented with the major current transports identified by longitude where they cross each section along with an extensive table of the inverse model mass, heat and freshwater transports. The paper which represents a substantial set of work and will be a useful future reference should be published.
There are however several pieces of missing information from the paper, and also the text presentation needs to be improved in places.

Thank you for your thorough revision. We have answered and considered all your questions and comments, and as result the manuscript has improved significantly.

Main things that need further discussion are;

- *Details of when the actual sections used were taken. Currently we are simply told if section was taken in each decade. A table of the sections used with their woce/go-ship identifications and the dates could be used.*

We agree that there could be more information regarding the sections used. Therefore, we have included a column for the specific dates of the cruises and their WOCE/GO-SHIP identification names in Table 1. We are not able to include a more detailed description of each section in this study, but vertical sections of temperature and salinity for each cruise are available in the Supporting Information of Caínzos et al. (2022). This information has been included in the text:

Lines 118-120: "**Table 1** summarizes the chosen sections and their characteristics, as well as the period when data were collected. Vertical sections for temperature and salinity for each cruise are available in the Supporting Information of Caínzos et al. (2022)."

- *More explicit statements about how the uncertainties from the inverse solution currents are derived and what they represent. What has been assumed about uncertainties in the input data? The uncertainties in the output are presented as if these really represent the uncertainties in a decadal mean current. But key assumptions have been made in particular that the current systems are in steady state because they are only being sampled once? and these latitude samples are all at different times. These are well known issues with steady inverse models but the caveats need to be clearly stated. I suggest that an additional paragraph relevant to these issues can be added after L155 stating important caveats to interpreting results.*

As the reviewer has stated, the use of inverse results is associated to certain issues that we have now stated in the text:

Lines 157-169: "The Gauss-Markov estimator is applied to solve this highly underdetermined system of equations (Wunsch, 1996) with a minimum error variance solution from the initial estimates of the unknowns - the velocities at the reference level (**b**) and the adjustments to the

Ekman transport (ΔT_{Ek}). To solve it, we first need a priori estimates and uncertainties that give an initial approximation to the actual value. Despite obtaining similar results, this study provides smaller uncertainties than other global inverse solutions (Ganachaud, 2003b) and decadal studies (Fu et al., 2020). This was achieved by using physical constraints with a simpler model with only the velocities at the reference level and the Ekman adjustments as unknowns. However, we have to be aware that there are some limitations associated with inverse modeling of hydrographic data, as inverse models with single-section snapshots are presumably subject to aliasing (Frajka-Williams et al., 2019; Wunsch and Heimbach, 2006). Therefore, each inverse solution could be interpreted as representative of a relatively short time interval (Fu et al., 2020) or could give information of monthly variations of the AMOC (Bryden et al., 2005b). Ganachaud (2003a) refer to their estimates as time-average transoceanic transports with realistic uncertainties, although they acknowledge the temporal sampling problem inherent to the discrete sampling of hydrographic data. Therefore, the validity of hydrographic data to reconstruct climatological estimates is an open debate."

- *Heat and Freshwater transports are given for each separate current component. It should be stated how these are defined because these are not formally separable from the mass transport.*

Thank you, we have included the definitions for the heat and freshwater transports in the text.

Lines 181-189: "Heat transport (T_H) can be computed as

$$T_H = \int c_p\, \theta\, \rho\, (v_r + b)\, dA, \quad (3)$$

where c_p is the heat capacity of sea water and θ is the potential temperature.

The freshwater flux (FW) has been estimated as the freshwater divergence, which represents the difference between the total freshwater flux and the volume flux through the Bering Strait (Caínzos et al., 2022; McDonagh et al., 2015; Bryden et al., 2011):

$$FW = -\frac{T_i^M S' - \int \rho\, S'\, (v_r + b)\, dA}{S_0}, \quad (4)$$

where T_i^M is the interbasin mass transport, i.e., across the Bering Strait (-0.8 Sv), S' is the salinity anomaly and S_0 is the area-weighted section average."

- *There is virtually no proper discussion of water mass transformation between sections? Lines 397 are randomly introduced but a little more clear discussion would be useful. I appreciate that this is not the main subject of the paper but since the water masses and currents are being defined by their density classes and the transport strengths are changing as currents cross different latitudes it would be useful to be given some of this information where large transformations between classes are being derived by the inverse analysis. A standard way to do this would be to add some up/down arrows on figure 7,8 or 9 to show conversions between upper, intermediate and deep waters*

As stated by the referee, this is not the original focus of the paper. It has been explored in more detail in a previous paper attending to the balance in mass transport across each section (Caínzos et al., 2022). In this manuscript, we have profited from these results in only certain occasions, as the computation is not as straightforward when describing the diapycnal transformations between individual currents. In the case of the subpolar north Atlantic, we were able to determine it due to the extension and latitudinal continuity of the NAC, but that is a rare case. Therefore, attending to individual currents, we would not be able to quantify these vertical transformations and only two or three vertical arrows could only be added to the figure. Thus, we consider that it would not help to improve the manuscript.

- *The current schematic figures 7,8,9 are very useful but are not referenced in text where the current details are discussed. I suggest Figs 7,8,9 are moved up to be introduced as summary results near the start and then references should be included to these figures in the text at the same time and the transport sections are discussed as the geographic referencing would greatly help understand the connections between sections.*

Thank you very much for your suggestion. We have followed it and introduced figures 7, 8 and 9 at the beginning of the Results section and referenced them throughout the section.

Lines 197-200: "This study uses a combination of hydrographic sections taken over the course of thirty years to describe the intricate network of currents that make up the AMOC throughout the Atlantic basin. With the results from the inverse models, we can measure the main important currents that flow along the Atlantic Ocean. Here we assess their transport in terms of mass (**Figure 2**), heat (**Figure 3**), and freshwater transport (**Figure 4**)."

More minor point by point issues are listed below;

Line 87 assumed level of no motion. This is not "known".

Thank you, we have changed the text to "assumed level of no motion".

L95 It is not a "fact" that currents are close to a steady time mean. It is an "assumption". This assumption is a very large caveat on the uncertainty values.

The reviewer is right, and, therefore, we have changed "fact" for "assumption". We have included in the manuscript a more detailed description of the uncertainties, stating the issues related to the representativeness of the results obtained (as discussed in the second main point above).

L122 Does the reference depth vary with longitude?

As the reviewer has pointed out, the value of reference depth may change with longitude along a section. As written in the manuscript, we have chosen a neutral density as reference layer to integrate the thermal wind equation. Therefore, this layer remains the same in a neutral density framework despite changing in depth.

L175 Are quoted MC transports the average over 3 decades?

In this case, only results for the 1990-99 decade are available for the MC at 45°S. However, it is true that we had not stated that in the manuscript, which we have rectified now by introducing the time range in the paragraph:

Lines 173-175: "The MC is observed as a northward transport of 37.2 ± 2.0 Sv at 45°S over the platform and slope of the 1990-99 inverse solutions (**Figure 2**), extending 109 km from the coast to 58.6°W (**Figure 5 l, m** and **Table 2**)."

L244 The longitudinal extent and widths quoted for many currents (eg. BeC here) are not so easy to decide upon from the transport sections. Often the main currents seem to occupy much smaller widths. This often leads to very different widths being identified for different decades. A clearer statement about how these ranges are defined would be helpful. L360, L507, L564 other examples. In L633 for example there seem to be large + and – values which cancel out and a very small value is given in text over a large extent?

Thank you for your suggestion. Following your and Reviewer 2's suggestions, we have now acknowledged in the manuscript the description of these ranges. Our definition for the longitudinal ranges for each current is based on the eastward accumulated horizontal transport, generally depicted in the middle panels of figures 5 to 9. For each of the layers defined between neutral density (γ^n) surfaces, we observe their behaviour on the area where the literature has often situated each of the currents studied here. We then define the extension within certain pairs of stations that present a similar slope in the eastward horizontal accumulated mass transport and delimit their range in the vertical by neutral density interfaces with the same flow direction. Therefore, we present a more experimental approach attending

to the mass transports obtained between each pair of stations for each of the 11 neutral density layers. We have tried to convey this in the manuscript as following:
Lines 190-192: "The longitudinal extension of each current has been defined based on the eastward accumulated horizontal mass transport, defining the chosen station pairs with a consistent slope in the accumulated horizontal mass transport. The vertical extension is ascribed with the net mass transport integrated over the chosen station pairs with the same flow direction."

L259-262 The paragraph structure is very unclear. Some are very long some very short (as here) Some more thought about what should be in each paragraph is needed throughout to help readability.
Thank you for pointing this out. Originally, we tried to present a paragraph for each of the sections where we could see a current and, when possible, a final paragraph comparing their evolution in time or in space. But that indeed resulted in paragraphs with different length.
We have tried to fix this issue throughout the manuscript, reorganizing the structure of the paragraphs.

L337 750m is not very shallow??
The deeper level of the CC has been found at similar depths in previous studies (Machín et al., 2006; Comas-Rodríguez et al., 2011; Pérez-Hernández et al., 2013; Hernández-Guerra et al., 2017; Casanova-Masjoan et al., 2020; Pérez-Hernández et al., 2023). To avoid confusion regarding its depth, we have removed the term 'relatively shallow' from the text.
Lines 377-378: "The CC flows along the first ~750 m of the water columna (Pérez-Hernández et al., 2013; Hernández-Guerra et al., 2017; Casanova-Masjoan et al., 2020) from the surface to 27.23 kg m^{-3}…"

L365-367 Notice the very large uncertainties given in other literature relative to tiny uncertainties you are giving. This is clear example of where the main point 2 above needs more careful discussion.
We appreciate your observation and have extended the description of the uncertainties (discussed above).

L416 low relative to what?
You are right. We were referring to the higher values of the IC, but it does not make sense written in this way, as IC is mentioned later. We have thus removed the term 'relatively' from the manuscript.
Line 458: "We have found low values of mass transport for the southward flowing ERRC".

L464 The section figures always use 55N as the average latitude but the text always uses 58N. Perhaps be consistent?
Thank you for pointing this issue out. In general, we have tried to use 55°N when referring to the section formed by the combination of the western and eastern basins (AR07W+AR07E). In the manuscript, they are mainly cited separately: 53°N for the western basin and 58°N for the eastern basin. In line 464, we were referring to the eastern portion of the section, and that is why we have used 58°N. As this can be a bit confusing, we have tried to include 53+58°N in the figures, rather than 55°N. The remaining references to 55°N are related to other studies that use 55°N. Moreover, in the paragraph describing the sections used, we have added a bit of explanation to define the nominal latitudes:
Lines 115-119: "Deviations of some stations from the nominal latitude appear mostly over the western and eastern boundaries and over the platform, correcting the track line to a perpendicular angle to the main current. Only three sections appear in all three decades: 30°S, 24.5°N and the northernmost sections (at an average latitude of 55°N) divided into the western (53°N) and eastern (58°N) basins."

L488-91 repetitive of Brearley result

The reviewer is right. We have mentioned Brearley's results twice. We have thus removed the first sentence, leaving only the following:

Lines 534-535: "Hydrographic sections over different summers at the Denmark Strait yielded -4.9 ± 0.5 Sv southward (Brearley et al., 2012), ...".

L512 Sometimes hugely different values are obtained in previous literature. These are cases where some suggested explanation would be useful?

The reviewer is right, we sometimes encounter different values compared to the literature. For the deep-water transport out of the Labrador Sea, the flow has a strong barotropic component (Fischer et al., 2004, 2010; Zantopp et al., 2017) that cannot be resolved with inverse models. A possible solution to estimate this barotropic component would be using LADCP or SADCP direct velocity measurements (Hernández-Guerra and Talley, 2016; Hernández-Guerra and Joyce, 2000; Casanova-Masjoan et al., 2018; Arumí-Planas et al., 2022). However, this kind of data is not often available. We have included this discussion in the manuscript, in the 'Methods' section regarding the inverse model, as well as for some of the comparisons with literature.

Lines 170-175: "Moreover, inverse models are able to resolve the circulation satisfactorily in most regions, except at subpolar latitudes where the barotropic component of the current is strong and the velocity at the reference level from the inverse model does not take into account this barotropic velocity (Álvarez et al., 2002). Therefore, mass transports in these regions can be underestimated. This issue could be resolved with the use of LADCP/SADCP direct velocity measurements capturing this barotropic component, but these data are not often available (Hernández-Guerra and Talley, 2016; Casanova-Masjoan et al., 2018; Arumí-Planas et al., 2022; Lherminier et al., 2007, 2010; Holliday et al., 2018)."

Lines 556-557: "These differences may arise due to the strong barotropic component observed for this current that inverse solutions fail to resolve."

L540 East of DWBC?

We thank the reviewer for pointing out this issue. We have now removed from the text and tables the DWBC recirculation.

Lines 585-587: "West of the DWBC there is a recirculation that carries water northward at deep layers, previously estimated to be around 13 Sv using current metre moorings (Bryden et al., 2005a) and 8 Sv from CTD and LADCP profiles (Biló and Johns, 2020), despite the poorly defined zonal extent of the circulation."

L544 Still worth marking where you have taken data from on section

We agree with the reviewer it could have been useful, but now it is not necessary, as we have removed this feature of the DWBC from the results and discussion.

L654 In summary be very clear what surface intermediate and deep mean

Thank you very much. We have tried to clarify it in the manuscript.

Line 702-703: "Near 61 Sv of upper waters from surface, thermocline and intermediate layers enter the Atlantic basin ...".

L680 "Errors" often used when you mean "uncertainties"

Thank you, we have changed the term "errors" in the manuscript for "uncertainties".

L686 recuperation => recovery

Changed.

L690 upper => upward

Thank you for your suggestion, we have changed it in the manuscript.

L720 Care to comment on the importance or not of the FW transport into the Atlantic from the south vis a vis AMOC stability?

Thank you for pointing this out. This issue was not our goal for this study, as we have previously discussed it in Caínzos et al. (2022), but we agree that it could help paint a picture of the importance of freshwater in the South Atlantic. Thus, we have included a short statement on the matter in the 'Summary and conclusions'.

Lines 776-782: "In the South Atlantic, the overturning component of the freshwater flux (the baroclinic transport due to the zonally averaged vertical-meridional circulation) has been identified as a possible indicator of the stability of the AMOC (Dijkstra, 2007; Weijer et al., 2019; Rahmstorf, 1996). Assessing and monitoring the freshwater budget in the South Atlantic is an important tool in determining whether the Atlantic Ocean behaves with a monostable or bistable regime. The negative or positive sign of this overturning freshwater flux (either due to a southward or northward transport of freshwater in the southern boundary of the Atlantic Ocean, respectively) informs of the net precipitation or evaporation (respectively) over the basin."

Are you inverse solution transports available along sections as available datasets?? Along with density transformations presumably?

At the moment our results from the inverse solutions are not available as datasets but can be provided upon request. We have included this in the Data Availability Statement.

Lines 805-806: "Results from the inverse solutions can be provided upon request."

There are small grammatical/english issues through the manuscript which could be corrected by a more careful reading.

Thank you for your revision. We have read through the manuscript and have tried to correct any language issues we have found.

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