PL24A-2271: Weakening of the Atlantic Meridional Overturning Circulation Abyssal Limb in the North Atlantic

Tiago C. Biló[†,1,2], Renellys C. Perez[2], Shenfu Dong[2], William Johns[3], and Torsten Kanzow[4]

[†]tiago.bilo@noaa.gov; [1]UM/CIMAS, U.S.; [2]NOAA/AOML, U.S.; [3]UM/RSMAES, U.S.; [4]AWI, Germany

Introduction

Antarctic Bottom Water (AABW) comprises the world's oceans coldest and densest water masses. As it is formed through a myriad of physical processes along the Antarctic continent[1], it redistributes large amounts of heat and carbon within the northward-flowing deepest limb of the global Meridional Overturning Circulation (MOC)[2]. Although several studies have shown that the cold AABW layer has been continuously shrinking and warming in association with a possible slowing down of the abyssal MOC since the 1980s[3], abyssal cooling reports[4] put into question the persistence of these signals in the western North Atlantic basin in the 21[st] century.

Goal

Quantify the variability of the AABW inflow to the subtropical North Atlantic on interannual-to-longer time scales and associated abyssal temperature changes between 2000-2020.

Dataset

Observations at 16°N

- **MOVE moored hydrography records (2000-2020):** Two moorings equipped with MicroCAT recorders and two repeated CTD transects obtained in Feb. 2000 and 2002 between the moorings.
- **GAGE moored velocity records (2000-2002):** Nine moorings equipped with Vector Averaging Currentmeters.

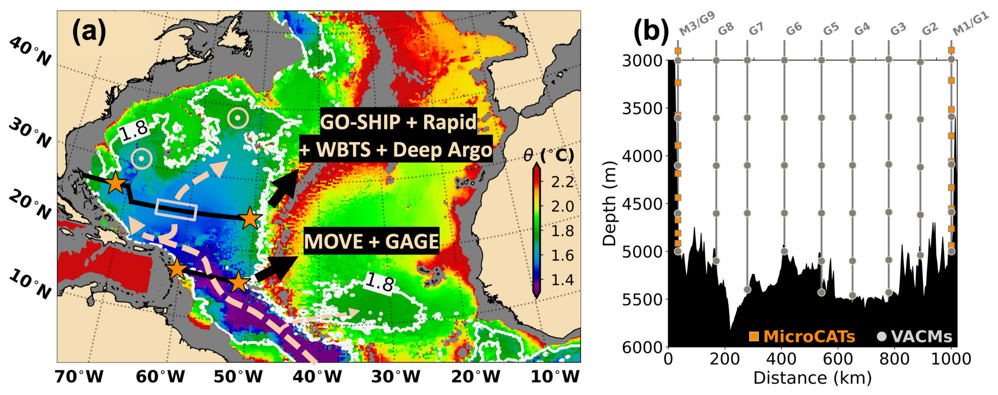


Figure 1: Dataset used in the present study and primary AABW pathways in the western North Atlantic. **(a)** WOA-18 near-bottom Potential Temperature (θ) in the North Atlantic tropical and subtropical regions overlayed with the AABW flow direction and deep upwelling areas from [5] (dashed arrows and circles, respectively). The stars and black lines indicate moorings and CTD hydrographic lines from the different observational programs, respectively. The gray box bounds the mid-basin area where Deep Argo profiles are present. **(b)** Schematic of the MOVE (M1 and M3) and GAGE (G1-G9) mooring arrays at 16°N and their typical instrumentation distribution below 3000 m across multiple deployments. Acronym VACMs stands for Vector Averaging Currentmeters.

Observations at 24.5-26.5°N

- **WOCE/GO-SHIP hydrography (1998-2020):** CTD profiles from six occupations of the historical A05 line.
- **NOAA's WBTS hydrography (2000-2021):** CTD profiles from 28 occupations of the repeated transect, spanning 70°W-77°W and near-bottom temperature records (depth∼5340 m) from a PIES' internal temperature sensor at 72°W.
- **Rapid hydrography (2004-2018):** CTD profiles from seven cruises servicing the Rapid-AMOC program moorings near the Mid-Atlantic Ridge (MAR) and moored near-bottom temperature (depth∼4820 m) at MAR's western flank (50°W, 24.5°N).
- **Deep Argo (2017-2021):** 36 temperature profiles from five Deep SOLO floats (Float Id# 4902323, 4902324, 6901214, 6903719, and 6903720) down to 6000 m depth.

Approach

- **AABW inflow to the Subtropical North Atlantic =** AABW transport across 16°N. AABW transport consists of the northward geostrophic transport of water colder than $\theta = 1.8$°C.
  1. **MOVE hydrographic moorings:** Dynamic height and geostrophic shear relative to 4500 m, or $\theta = 1.8$°C, between 4500-5000 m.
  2. **GAGE currentmeter moorings and CTD transects:** Zonally-averaged mean directly-observed (GAGE) and geostrophic (CTD transects) velocity profiles are used to extrapolate the MOVE vertical geostrophic shear below 5000 m. These observations suggested zero-flow at ∼5600-5800 m depth.
- **Abyssal temperature long-term changes in the first two decades of the 21st century**: Average subtropical North Atlantic temperature trends calculated using the collection of hydrographic observations at 24.5-26.6°N.
- **Abyssal ocean contributions to heat content and sea-level rise of the western North Atlantic**: World Ocean Atlas 2018 climatology and basin-wide warming at 24.5-26.5°N were used to obtain rough estimates of the AABW's volume change between 2000-2020 and its contribution to Ocean Heat Content (OHC) and Sea Level Rise (SLR).

1. AABW inflow to the subtropical North Atlantic has weakened in the past 20 years

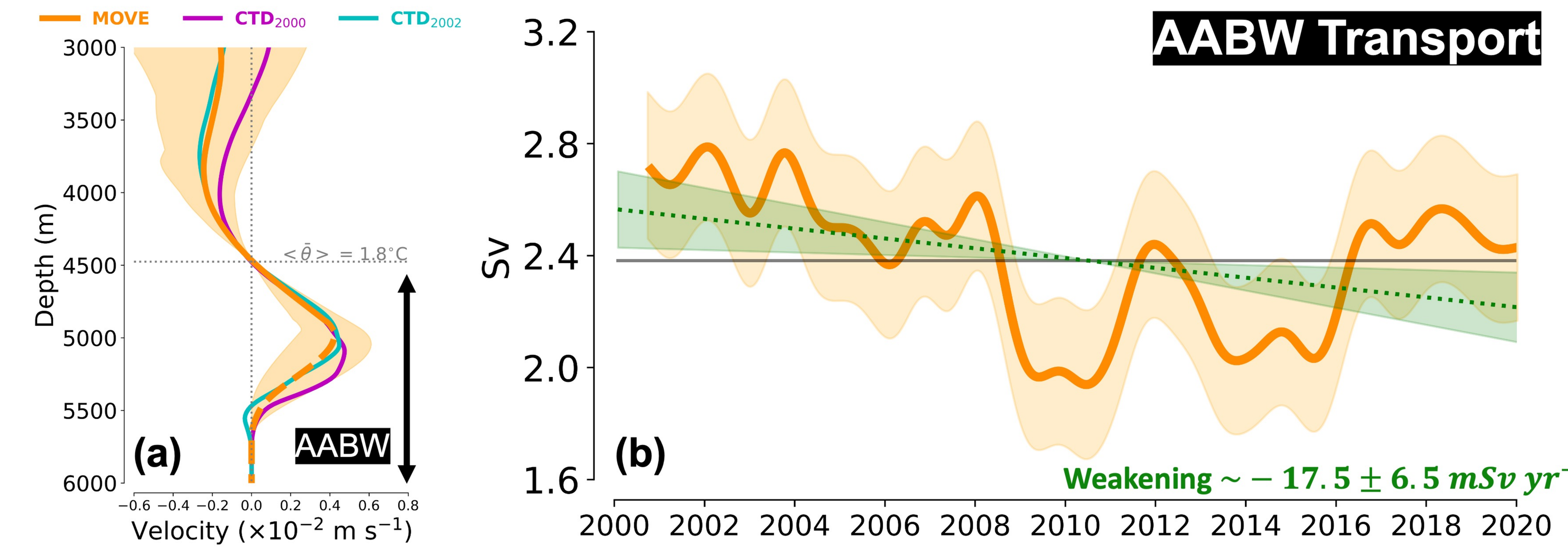


Figure 2: MOVE data analysis showing the mean AABW flow and its weakening across 16°N between 2000-2020. The mean AABW transport is 2.40±0.25 Sv. Over approximately 20 years, the AABW transport reduced by 0.35±0.13 Sv, corresponding to 12±5% of the annual mean transport in 2000. In addition, periods like 2008-2010 and 2016-2017 present strong transport changes of 0.65 and 0.50 Sv, respectively. **(a)** Mooring-based 2000-2020 mean (orange line) and CTD-based (magenta and cyan lines) geostrophic velocity profiles between the MOVE moorings. The dashed portion of the mooring-based profile shows where our vertical extrapolation scheme was applied. The shaded area is the mooring-based geostrophic velocity data range throughout the time series at each depth. **(b)** Eighteen-month low-passed filtered AABW geostrophic transports referenced at 4500m and integrated between 4500m and the bottom. Dotted lines and shaded areas represent the transport trends and the 95% confidence intervals of our calculations.

2. AABW flow weakening is associated with the shrinking of the AABW cold layer (i.e., $\theta < 1.8$°C)

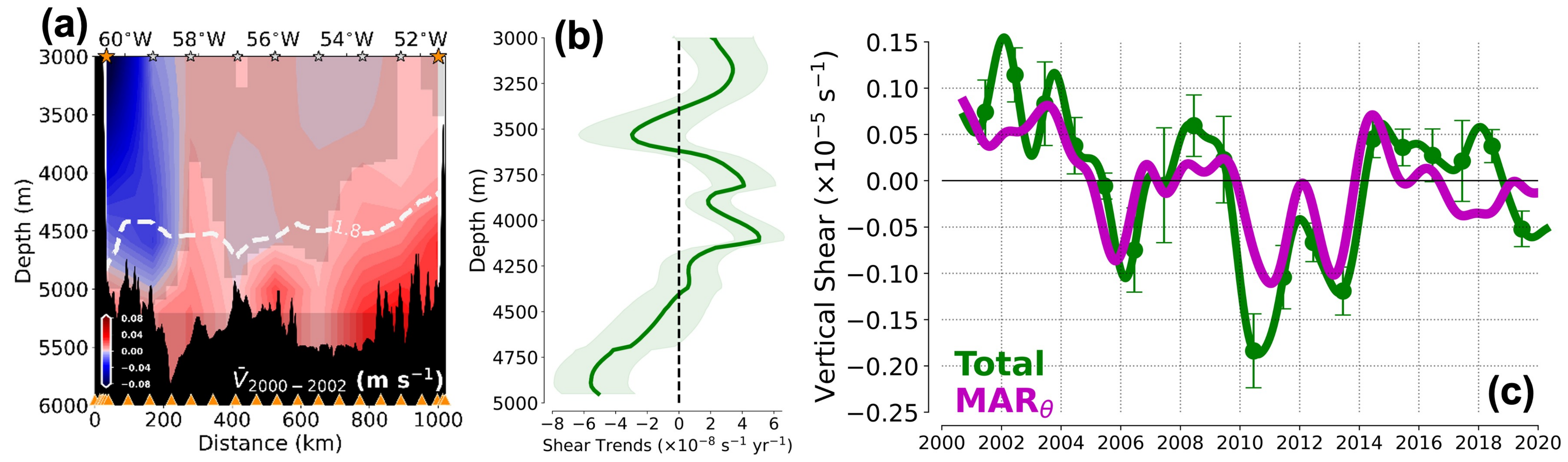
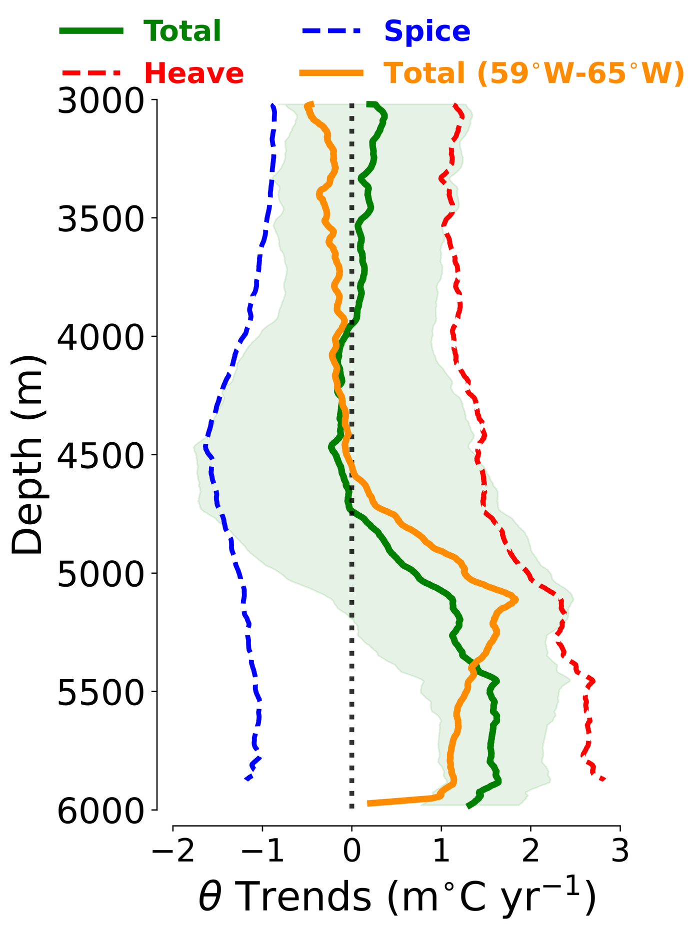


Figure 3: GAGE and MOVE data analyses show that the weakening of the AABW flow is associated with the shrinking of the AABW layer, which drives abyssal warming. Because we used a fixed reference level at 4500 m for geostrophic estimates, AABW transport variability is purely driven by the geostrophic shear (i.e., horizontal density gradients) variability below 4500 m. While (a) shows that the AABW flow is concentrated near the MAR, (b) and (c) show that the geostrophic shear trends can be explained by the AABW layer shrinking (i.e., isopycnal-heaving driven warming) near the MAR. **(a)** Cross-transect 2000-2002 mean velocity from the GAGE program overlayed with $\theta = 1.8$°C isotherm from the MOVE 2000 cruise. The dark shade indicates the areas where the mean velocity is not statistically different from zero within the 95% confidence interval. The triangles represent the MOVE CTD cast locations. Stars are the mooring locations seen in Figure 1b. **(b)** The 2000-2020 linear geostrophic shear trends between the MOVE moorings. Negative trends indicate the flattening of isopycnals. **(c)** Eighteen-month low-passed filtered abyssal geostrophic shear anomalies averaged between 4500-5000 m (solid green line) and its correspondent variability driven by the isopycnal-heaving temperature changes near the MAR (MAR$_\theta$, magenta dashed line). The trend in the green line can be explained in almost its entirety by the magenta lines present. Uncertainties in **(b)** and **(c)** represent the 95% confidence intervals.

3. AABW cold layer volume decrease contributes to the increase of the local abyssal OHC and SLR

- **Warming trends are constrained below 4500 m (i.e., AABW layer):** Similar to 16°N, the warming signal is driven by the shrinking of the AABW cold layer (i.e., isopycnal heaving).



- **Average 4500 m-bottom warming is ∼0.001°C yr^{-1}**
- **Over 20 years, a warming of 0.001°C yr^{-1} results in an AABW volumetric loss that is consistent with the mooring estimates (i.e., ΔV = 1-2×10^{14} m^3)**
- **Abyssal warming increased the western North Atlantic OHC by 0.49 ZJ accumulated over the past 20 years, contributing to SLR in approximately 2.8 mm due to water thermal expansion.**

Figure 4: Analysis of the hydrographic observations along 24.5°N-26.5°N showing the horizontally-averaged abyssal warming signal at the western North Atlantic. Figure shows the θ trends zonally-averaged across the basin along 24.5°N (solid green line), and its heave and spice components (red and blue dashed lines, respectively) overlayed with trends near the center of the basin (59°W-65°W, solid orange line), where Deep Argo profiles were available. The shaded area represents the 95% confidence interval of the total trend.

Summary and conclusions

AABW inflow to the subtropical North Atlantic

- The AABW flow at 16°N has decreased by 12% in approximately 20 years (2000-2020) associated with the AABW layer contraction
- AABW transport variability presents substantial interannual-to-decadal oscillations

AABW layer contraction in the subtropical North Atlantic

- Abyssal warming signal in the western North Atlantic persisted in the 21st century, contributing to local OHC and SLR
- Zonally-averaged warming rates are approximately half the rates found in the western South Atlantic Ocean along the AABW main pathways[6,7], suggesting a "dilution" of the signal as the AABW spreads northward
- The conflicting reports on the western North Atlantic abyssal warming after 2000 result from a relatively short time series at the time of those studies and the inclusion of areas with significant North Atlantic Deep Water content

References

1 Orsi, A.H., Johnson, G.C., Bullister, J.L.: Circulation, mixing, and production of Antarctic Bottom Water. Prog. Oceanog. **43**, 55–109 (1999). doi:10.1016/S0079-6611(99)00004-X

2 Lumpkin, R., Speer, K.: Global Ocean Meridional Overturning. J. Phys. Oceanogr. **37**, 2550–2562 (2007). doi:10.1175/JPO3130.1

3 Desbruyères, D.G., Purkey, S.G., McDonagh, E.L., Johnson, G.C., King, B.A.: Deep and abyssal ocean warming from 35 years of repeat hydrography. Geophys. Res. Lett. **43**, 10356–10365 (2016). doi:10.1002/2016GL070413

4 Desbruyères, D., McDonagh, E.L., King, B.A., Thierry, V.: Global and full-depth ocean temperature trends during the early twenty-first century from Argo and repeat hydrography. J. Climate **30**, 1985–1997 (2017). doi:10.1175/JCLI-D-16-0396.1

5 Talley, L.D., Pickard, G.L., Emery, W.J., Swift, J.H.: Descriptive Physical Oceanography: an Introduction, 6th edn. Academic Press, London (2011).

6 Johnson, G.C., Cadot, C., Lyman, J.M., McTaggart, K.E., Steffen, E.L.: Antarctic Bottom Water warming in the Brazil Basin: 1990s through 2020, from WOCE to deep Argo. Geophys. Res. Lett. **47** (2020). doi:10.1029/2020GL089191

7 Johnson, G.C.: Antarctic Bottom Water Warming and circulation slowdown in the Argentine Basin from analyses of deep Argo and historical shipboard temperature data. Geophys. Res. Lett. **49** (2022). doi:10.1029/2022GL100526

Acknowledgments

We thank the many scientists, engineers, and mariners from many institutions worldwide who supported several projects that developed instruments and collected, processed, and published the data we used in this work. T. C. B., R. P., and S. D. were funded by NOAA's Global Ocean Monitoring and Observing program (FundRef number 100007298); NOAA's Climate Program Office, Climate Observations and Monitoring, and Climate Variability and Predictability programs under NOFO NOAA-OAR-CPO-2021-2006389. AOML/NOAA provided additional support. W. J. we funded by the U.S. National Science Foundation under grants OCE-1332978 and OCE-1926008. T. K. is funded by the EU's Horizon 2020 Research and Innovation Program under the Grant agreement number 821001 (SO-CHIC), and therein is a contribution to its Work Packages 3 and 6. This study is further a contribution to the project T3 of the Collaborative Research Centre TRR 181 "Energy Transfers in Atmosphere and Ocean" funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation; project number 274762653). This research was carried out in part under the auspices of the CIMAS, a cooperative institute of UM and NOAA, cooperative agreement NA 20OAR4320472.