Deep Atlantic Multidecadal Variability

Jiajun Yang[1], Jianping Li[2*], and Qirong An[3]

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1. Background

- The ocean, a pivotal component of the Earth's system, assumes an irreplaceable role in the regulation of global warming, especially the deep sea (Figure 1) (Trenberth et al., 2016).

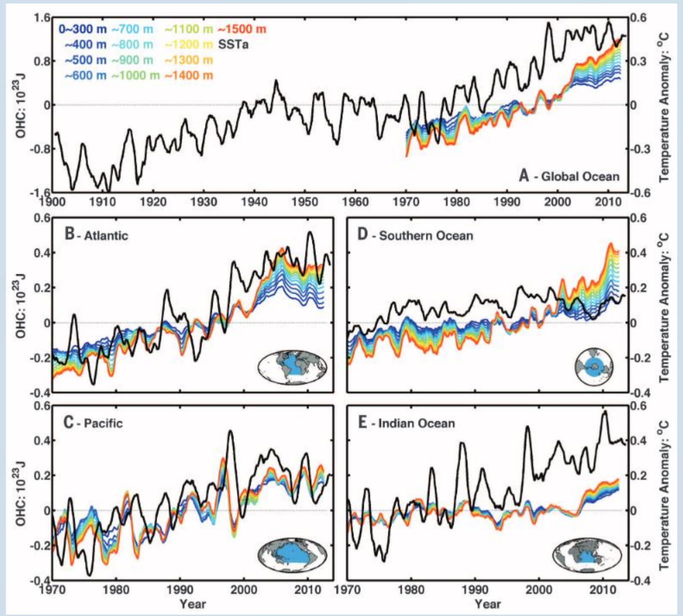

Figure 1 Integrated OHC from the surface to different indicated depths in the global ocean and different basins (Chen & Tung, 2014).

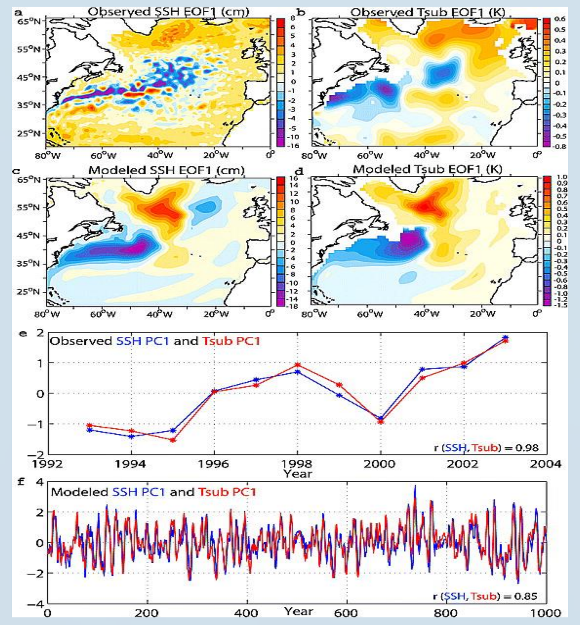

Figure 2 Observed and modeled annual mean anomalies of SSH and Tsub in the Atlantic (Zhang, 2008).

- A multitude of studies discuss the Atlantic Multidecadal Variability (AMV) in sea surface temperature (SST) (Sutton et al., 2018; Zhang et al., 2019). And several articles delve into the depth around 400 m manifesting a dipole pattern in the North Atlantic (Figure 2). However, only a limited number of studies focus on deep sea potential temperature (DSPT), especially at depths exceeding 1000 m, due to constraints from observation capability and climate model bias.
- Investigating the dominant mode of the deep Atlantic contributes to advancements in aquaculture, bioscience, and energy resources.

2. Data and Methods

Table 1 Summary of used data.

Variables	Unit	Domain	Period	Resolution	Source
Deep Sea Potential Tempera-ture (DSPT)	°C	90°N–83°S 180°W–180°E	1900.01–2022.12	1°×1°	**EN v4.2.2** *https://www.metoffice.gov.uk/hadobs/en4/download-en4-2-2.html*
		53°N Profile	2014–2018	Grid	**OSNAP** *Data access | OSNAP (o-snap.org)*
		34°S Profile	2004–2019	Grid	**SAMOC** *https://www.aoml.noaa.gov/phod/SAMOC_international/index.php*
		90°N–77.9°S 180°W–180°E	1958.01–2100.12	1°×1°	**ACCESS-OM2** *https://dapds00.nci.org.au/thredds/catalogs/cj50/access-om2*
		Global	500 years	1°×1°	**GFDL-ESM4** *https://aims2.llnl.gov/search/cmip6/*
		Global	1200 years	1°×1°	**CESM2** *https://aims2.llnl.gov/search/cmip6/*
AMV index	°C	the North Atlantic	1856.01–2022.12	Area Weighted Average	*https://psl.noaa.gov/data/timeseries/AMO/*

The AMOC fingerprints

The Atlantic Meridional Overturning Circulation (AMOC) stream function index is defined as the maximum overturning stream function at a special latitude (typically 30°N):

$$\psi(y,z)=\int_{x_{west}}^{x_{east}}dx\int_{z}^{\eta}v(x,y,z)dz$$

Meridional ocean heat transport

Meridional ocean heat transport (OHT) is calculated in a certain layer:

$$OHT(y)=\int_{x_{west}}^{x_{east}}\int_{-H_1}^{-H_2}\rho_0 C_p v(x,y,z)\theta(x,y,z)dzdx$$

3. DAMV in Observation

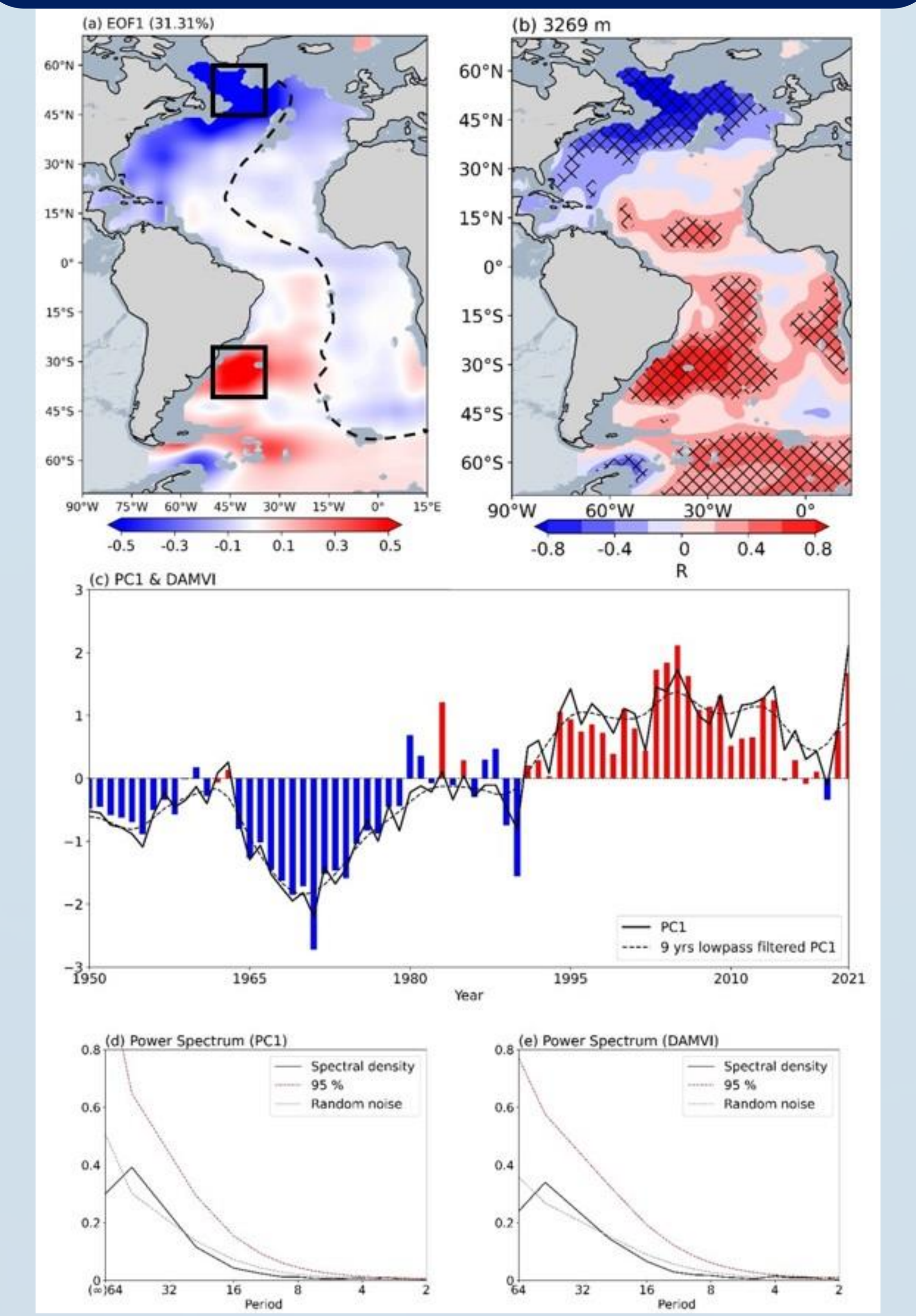

Figure 3 Spatio-temporal characteristics of the DAMV. (a) Spatial pattern of the DAMV. (b) The correlation map between the DAMVI and DSPT anomaly. (c) Standardized time series of the DAMVI (bar), the PC1 (solid) and its 9-years lowpass filtered (dashed). (d) Power spectrum of the PC1. (e) The same as (d), but for the DAMVI.

- **Spatial pattern**: A prominent north-south dipole pattern in the mid-high latitudes of the Atlantic basin (Figure 3a). Two pronounced loading centers: north key region (45°–60°N, 50°–35°W) and south key region (25°–40°S, 50°–35°W).
- **Temporal behavior**: A multidecadal variability with a range of meaningful quasi-period of 20–50 years (Figure 3c, 3d).

DAMV in close layers in observation:

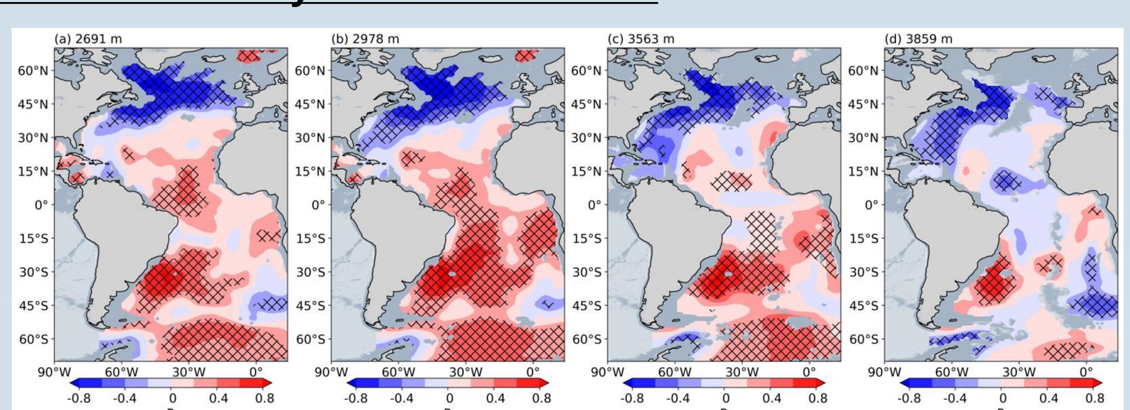

Figure 4 DAMV in close layers around 3000 m. The correlation map between the DAMVI and DSPT anomaly in: (a) 2691 m; (b) 2978 m; (c) 3563 m; (d) 3859 m.

- **Robustness in close layers**: DAMV could be discovered in observation from 2500 m to 4000 m or so (Figure 4), enhancing the robustness of DAMV.

4. Physical Interpretation of DAMV Based on the AMOC

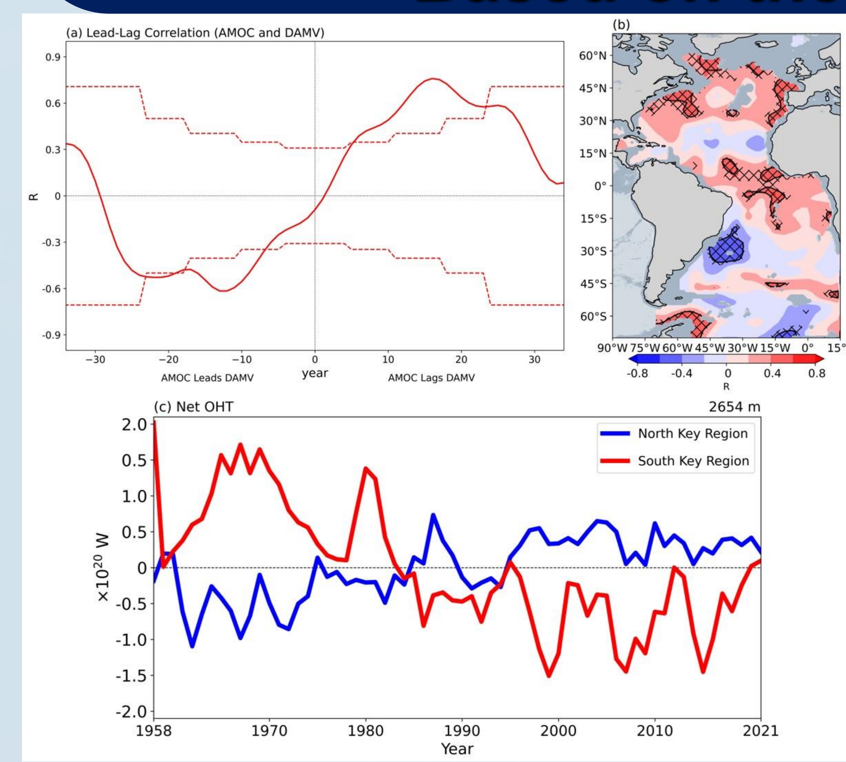

Figure 5 Relationship between the DAMVI and the AMOC fingerprints. (a) Lead-lag correlation between the 9-years lowpass filtered DAMVI and 9-years lowpass filtered AMOC stream function index. (b) The lead correlation map about the AMOC stream function index leading the DSPT anomaly 13 years. (c) Time series of net meridional OHT in two key regions of DAMV in the ACCESS-OM2.

- **Statistic relationship**: the AMOC may have association with DAMV, both in timescale and in spatial pattern presumably (Figure 5a, 5b).
- **Physical processes**: Net meridional OHT in key regions is defined as the meridional OHT at the northern boundary minus that at the southern boundary, which can well-match spatio-temporal features of the DAMV (Figure 5c).

Therefore, the AMOC acts as a dynamic driver in variation of the DAMV with high probability. And the DAMV is likely to be key for understanding the processes of deep Atlantic heat transport driven by the AMOC.

5. Model Evidences to Improve the Robustness of DAMV

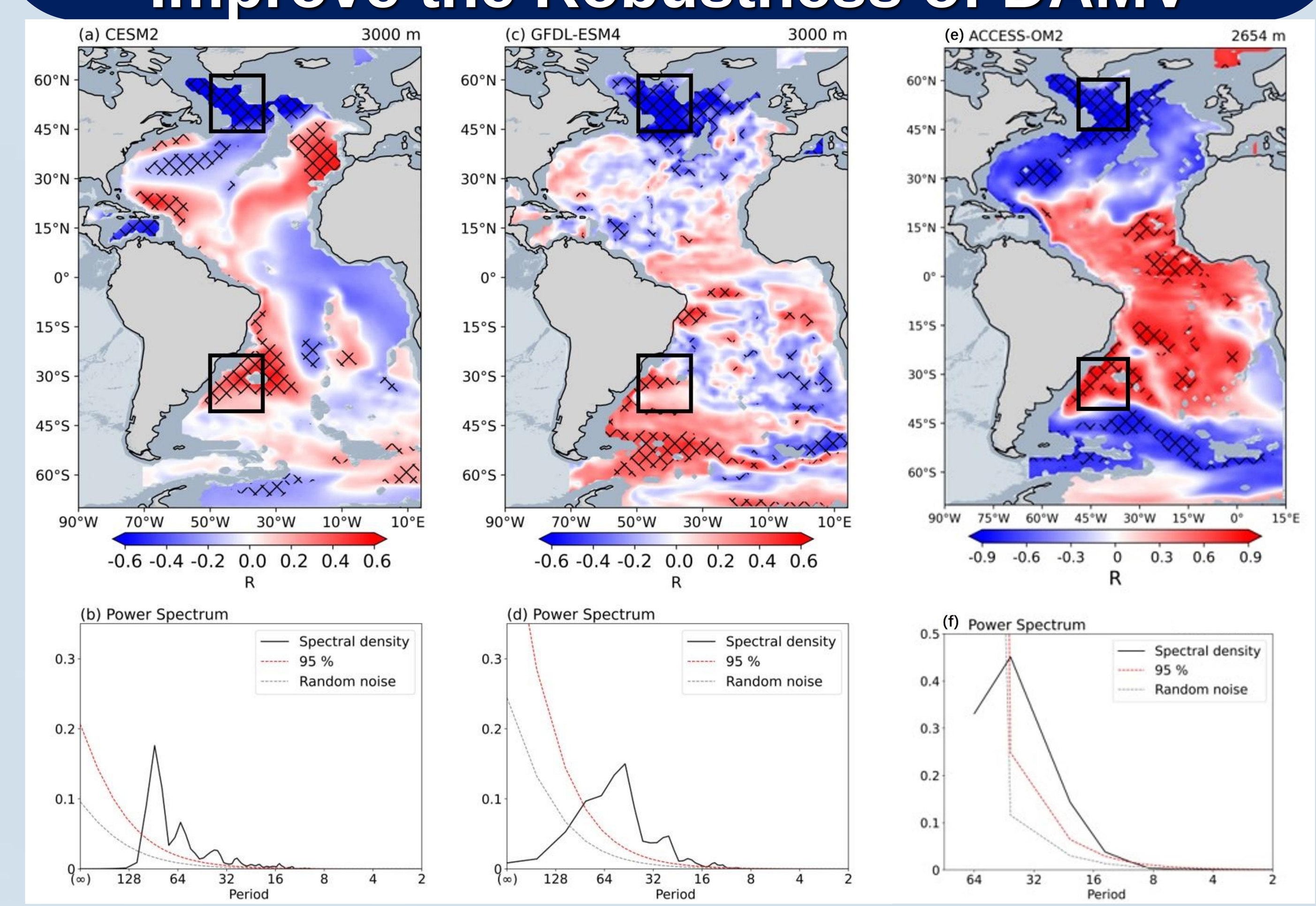

Figure 6 DAMV in two CMIP6 PiControl simulations (left: CESM2 in 1200 years; middle: GFDL-ESM4 in 500 years) and one ocean model simulation (right: ACCESS-OM2 in 142 years). The correlation maps between the DAMVI and the DSPT anomaly in three models are on the top, and their power spectrums of DAMVI are on the bottom.

- **Robustness in a variety of models**: DAMV could be identified among the 142 years ocean model simulation, 500 years and 1200 years climate models PiControl simulations (Figure 6), improving the robustness of DAMV.

6. Conclusions and Uncertainties

Conclusions:

- The dominant mode of the Atlantic DSPT is DAMV displaying a mid-high latitudes north-south dipole pattern with quasi-period of 20-50 years.
- The meridional ocean heat transport, driven by the AMOC, can well-explain the DAMV variation with high probability.

Uncertainties:

- The observation-only dataset of DSPT is shorter and scarcer compared with SST datasets. Hence, the uncertainty of deep sea dataset used in this study remains indeed.
- The DAMV deserves to be investigated by more model-simulated datasets with longer time span improving the robustness of conclusions.

Validity of the EN4 DSPT data:

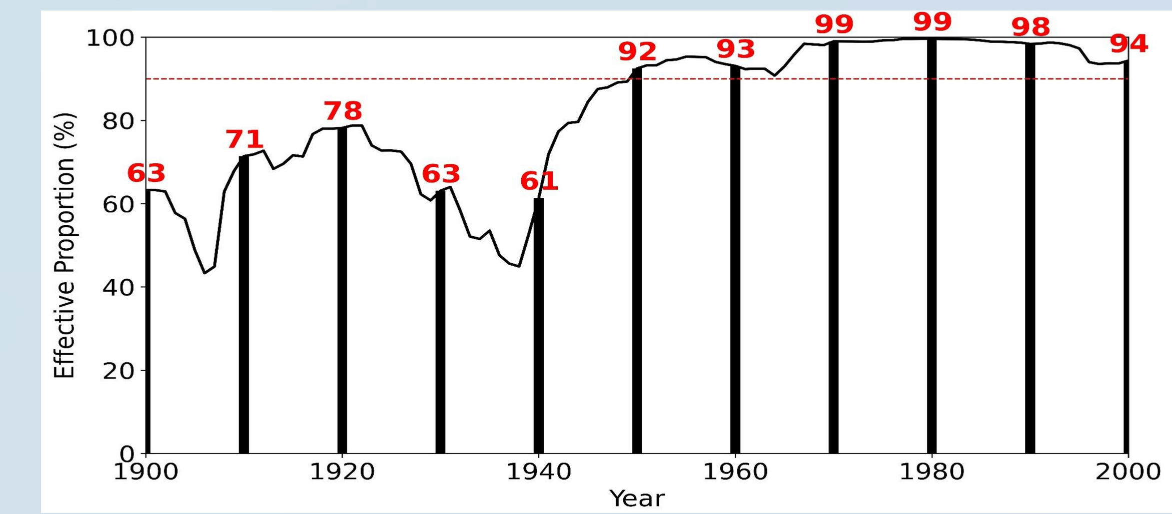

Figure 7 Effective proportion of the DSPT grid data in the Atlantic basin from the EN4 dataset from 1900 to 2000 in black and at each decade in bar.

- **Effectiveness**: The effective grid proportion in the Atlantic basin has reached up to 90%, indicating original DSPT data is effective to explore the dominant modes since 1950 (Figure 7).
- **Accuracy**: By the Haversine formula, a comparison is drawn between the gridded observational DSPT time series from 2014 to 2018 and the closest EN4 gridded time series.
  a) Average relative error at each grid point is 4.64% for the OSNAP and 5.31% for the SAMOC.
  b) Root mean square error records 0.095 for the OSNAP and 0.096 for the SAMOC.
  c) Average correlation coefficient for the OSNAP is 0.80 and for the SAMOC is 0.52

Overall, the EN4 dataset can be used to investigate the deep Atlantic in some way in consideration of the effectiveness and accuracy of DSPT dataset.

7. Authors and Reference

Authors:
1. Ph.D. Candidate, Academy of Future Ocean, Ocean University of China, China, yjj@stu.ouc.edu.cn
2. Professor, Key Laboratory of Physical Oceanography, Ocean University of China, China, ljp@ouc.edu.cn
3. Ph.D. Candidate, Academy of Future Ocean, Ocean University of China, China, angelan98@163.com

Yang, J., Li, J., & An, Q. (2024). Deep Atlantic multidecadal variability. Geophysical Research Letters, 51, e2023GL106367.