A Report on “Equatorial Atlantic Mid-depth Warming Indicates Atlantic Meridional Overturning Circulation Slowdown” by Ren et al. (2025)

Reviewer 2

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> I am wiser than this person; for it is likely that neither of us knows anything fine and good, but he thinks he knows something when he does not know it, whereas I, just as I do not know, do not think I know, either. I seem, then, to be wiser than him in this small way, at least: that what I do not know, I do not think I know, either.
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> Plato, *The Apology of Socrates*, 21d

> To err is human. All human knowledge is fallible and therefore uncertain. It follows that we must distinguish sharply between truth and certainty. That to err is human means not only that we must constantly struggle against error, but also that, even when we have taken the greatest care, we cannot be completely certain that we have not made a mistake.
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> Karl Popper, 'Knowledge and the Shaping of Reality'

Overview

Citation: Ren, Q., Xie, S.-P., Peng, Q., Li, Y., & Wang, F. (2025). Equatorial Atlantic Mid-depth Warming Indicates Atlantic Meridional Overturning Circulation Slowdown. *Communications Earth & Environment*, Vol. 6, No. 819.

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Abstract Summary: The study identifies a distinctive mid-depth (1000-2000 m) warming fingerprint in the equatorial Atlantic that signals a slowdown of the Atlantic Meridional Overturning Circulation (AMOC) via baroclinic Kelvin waves. Analysis of climate models and observations suggests this mid-depth warming is a more reliable indicator than surface proxies and indicates the AMOC slowdown already started in the late 20th century.

Key Methodology: Numerical ocean general circulation model (OGCM) experiments (MITgcm), analysis of a large ensemble of a Community Earth System Model (CESM2-LENS), and analysis of multiple observational datasets (Argo, WOA, IAP, Ishii, EN4, CCHDO) were used to identify and validate the temperature fingerprint.

Research Question: Can a distinctive temperature fingerprint in the equatorial Atlantic be identified to reliably signal the Atlantic Meridional Overturning Circulation (AMOC) change, and when did the AMOC slowdown begin?

Summary

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Ren et al. present a compelling case for a new diagnostic "fingerprint" to detect changes in the Atlantic Meridional Overturning Circulation (AMOC). Their central premise is that the traditional proxy—sea surface temperature in the subpolar North Atlantic—is too contaminated by atmospheric noise to be reliable on decadal timescales. Instead, they propose that a mid-depth warming (1000–2000 m) in the equatorial Atlantic serves as a "superior fingerprint" with a higher signal-to-noise ratio. By analyzing this signal in historical data, the authors claim the AMOC slowdown "already started in the late 20th century," estimating a weakening of approximately 2 Sv since the 1950s.

The study's theoretical core is highly credible. The authors use Ocean General Circulation Model experiments to isolate the physical mechanism: a slowdown in the AMOC triggers baroclinic Kelvin waves that propagate southward along the boundary and then eastward along the equator. This dynamic adjustment results in a specific vertical structure of warming that is distinct from surface variability. The logic here is sound and grounded in established geophysical fluid dynamics. The identification of the 1000–2000 m layer as the "sweet spot" for detection—where the signal is strong and surface noise is minimal—is well-supported by their signal-to-noise analyses (p. 4).

The observational evidence for the warming itself appears robust. Despite the known limitations of oceanographic sampling prior to the Argo era (post-2000), the authors demonstrate consistency across multiple gridded datasets (WOA, IAP, Ishii, EN4) and validate these against high-quality hydrographic transects (p. 4). The calculation of a "Time of Emergence" (ToE) around 2001 $\pm$ 6 is statistically rigorous, relying on a signal-to-noise threshold of 4 to ensure high confidence (p. 5).

This provides strong empirical support for the claim that the equatorial Atlantic has warmed significantly at depth, a trend that stands apart from natural variability.

However, the quantitative translation of this warming into a specific AMOC reduction (the "2 Sv" figure) requires more caution. This estimate is derived by applying a linear regression slope obtained from a single climate model ensemble (CESM2-LENS) to the observed temperature change (p. 7). This creates a significant dependency on the physics of that specific model. If the model's sensitivity—the amount of warming generated per unit of AMOC slowdown—differs from the real ocean, the 2 Sv estimate will be biased. This is particularly relevant because the authors explicitly note a discrepancy between the model and observations regarding the *timing* of the slowdown; the models suggest a later onset due to the offsetting effects of aerosols and greenhouse gases (p. 7). While the authors argue this discrepancy implies the real-world AMOC is more sensitive or responding to forcings (like meltwater) missing from the models, relying on a model that does not perfectly reproduce historical trends to quantify those same trends introduces a layer of epistemic uncertainty.

Ultimately, the qualitative claims are credible: the equatorial mid-depths are warming, this warming is dynamically consistent with an AMOC slowdown, and the signal has emerged from the noise of natural variability. The proposed proxy is a valuable contribution that likely offers a clearer view of ocean circulation changes than surface metrics. The specific quantitative magnitude of the slowdown, however, should be viewed as a model-dependent estimate rather than a direct measurement.

The Bottom Line

The identification of mid-depth equatorial warming as a robust, low-noise fingerprint for AMOC changes is credible and physically sound. The article presents convincing evidence that this warming signal has emerged from natural variability, strongly suggesting that an AMOC slowdown began in the late 20th century. However, the specific estimate of a ~2 Sv reduction relies on a calibration from a single climate model that may not perfectly capture real-world sensitivities, and thus should be treated as an approximation rather than a precise measurement.

Potential Issues

Model dependency of the quantitative slowdown estimate: The article's central quantitative conclusion—an Atlantic Meridional Overturning Circulation (AMOC) slowdown of approximately 2 Sv since the 1950s—is derived from a regression slope calculated using a single large model ensemble, the CESM2-LENS (p. 7). While the authors justify this choice by noting that a large ensemble is better suited for isolating the forced climate signal from internal variability, this approach makes the final number dependent on the specific physics and sensitivity of the CESM2 model. The article also presents results from a multi-model CMIP6 ensemble, which shows a robust correlation between the AMOC and the new proxy, but it does not use the CMIP6 ensemble to derive the quantitative slope applied to observations (p. 4, Supplementary Fig. 8). If the CESM2 model's sensitivity differs from the multi-model mean, the "2 Sv" estimate could be biased. This choice represents a trade-off between reducing uncertainty from internal variability (by using a large ensemble) and accounting for uncertainty in model structure (by using a multi-model ensemble), and the article's quantitative claim rests on the former.

Discrepancy between modeled and observed historical trends: The article's argument relies on applying a physical relationship derived from climate models to historical observations. However, the text explicitly acknowledges a significant discrepancy in the timing and behavior of the trends themselves. While observations show a "robust mid-depth warming since 1960," the climate models, including CESM2-LENS, show that the AMOC only "began to weaken sharply as anthropogenic greenhouse forcing overtook aerosol forcing" after the 1980s (p. 4). The authors attribute this model-observation mismatch to missing forcings in the models, such as meltwater from the Arctic, and the offsetting effects of aerosols and greenhouse gases (p. 7). The article's logic uses this discrepancy to argue that the real-world AMOC slowdown likely began earlier than models suggest. While this is a plausible interpretation, it means the quantitative inference is based on a model relationship that is applied to an observational record whose temporal evolution is not well reproduced by the same model.

Reliance on sparse early observational data: The conclusion that mid-depth warming began around 1960 is based on historical ocean datasets that are known to be sparse and uncertain, particularly before the widespread deployment of Argo floats in the early 2000s. The article acknowledges this limitation, stating that "the sparse observational sampling prior to 1980 introduces considerable uncertainty" (p. 7). To address this, the authors demonstrate that the warming signal is consistent across multiple gridded datasets (WOA, IAP, Ishii, EN4) and that these gridded products align well with high-quality, albeit spatially and temporally limited, ship-based transects from the CCHDO program (p. 4, Fig. 4e). While these robustness checks increase confidence in the historical signal, the inherent quality limitations of the early data remain a source of uncertainty for the article's historical claims.

Potential sensitivity of the time of emergence calculation: The article reports a precise "Time of Emergence" (ToE) for the mid-depth warming signal of 2001 $\pm$ 6 years, defined as the point when the signal-to-noise ratio exceeds a threshold of 4 (p. 5). Such calculations can be sensitive to the statistical definitions of "signal" and "noise." The authors address this to some extent by testing two different methods for defining the signal (a linear trend versus a 10-year running mean) and report that they yield similar results (p. 5). The chosen signal-to-noise threshold of 4 is justified as corresponding to a high (99.9%) confidence level. Nonetheless, the ToE metric is an interpretation of a continuous process, and its precise timing may be sensitive to the specific statistical methods employed, particularly when applied to datasets with known historical uncertainties.

Minor clerical discrepancy in model counts: There is a minor inconsistency in the number of models cited between different parts of the methodology. The Methods section states that the surface forcing fields used to drive the ocean-only model experiments were derived from the multi-model mean of “30 models from CMIP6” (p. 7). However, the analysis of the fully coupled model behavior, presented in the main text and Supplementary Figure 8, is based on “18 CMIP6 models” (p. 4). This difference is likely due to data availability for the specific variables required for each task and does not appear to affect the article’s conclusions, but the discrepancy is not explicitly explained.

Future Research

Multi-model sensitivity calibration: Future work should assess the relationship between equatorial mid-depth temperature and AMOC strength across a broader range of CMIP6 models, rather than relying primarily on the CESM2 ensemble for the quantitative regression. Establishing a probability distribution of the "conversion factor" (temperature change per Sv of slowdown) across different model physics would provide a more robust error margin for the 2 Sv estimate and reduce the reliance on a single model's stratification and viscosity parameters.

Integration of meltwater forcing: Given the authors' hypothesis that the discrepancy between modeled and observed timing may stem from the lack of Arctic meltwater in current simulations, future research should focus on "hosing" experiments or models that explicitly resolve ice sheet runoff. Simulating the specific impact of realistic freshwater input on the propagation speed and amplitude of the equatorial Kelvin waves would refine the Time of Emergence calculations and potentially resolve the mismatch in the onset of the slowdown.

Paleoceanographic validation: To validate the proxy on longer timescales, researchers could investigate high-resolution paleoceanographic records (e.g., deep-sea corals or sediment cores) from the equatorial Atlantic at the 1000–2000 m depth range. Correlating these proxies with established AMOC reconstructions from the North Atlantic during past abrupt climate change events (such as the Little Ice Age or Holocene fluctuations) would test the robustness of the mid-depth warming fingerprint beyond the short instrumental record.

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