

Observation-Based Early-Warning Signals of Atlantic Meridional Overturning Circulation Instability under Contemporary Climate Warming

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ABSTRACT

The Atlantic Meridional Overturning Circulation (AMOC) constitutes a central component of the global climate system, influencing large-scale heat transport, regional climate variability, and long-term climate stability. Recent observational and modeling studies increasingly suggest that the AMOC may be approaching a critical transition, potentially associated with nonlinear dynamical behavior and abrupt weakening. This study synthesizes observation-based methodologies for detecting early-warning signals of AMOC instability using global and regional temperature datasets, statistical indicators of critical slowing down, and advanced spectral estimation techniques. Drawing on surface temperature reconstructions such as GISTEMP and HadCRUT5, the analysis emphasizes the role of variance, autocorrelation, and low-frequency spectral power as indicators of reduced system resilience. Particular attention is given to methodological challenges arising from non-stationarity, seasonal effects, and heteroscedasticity in climate time series. By integrating maximum entropy spectral analysis with heteroscedasticity-robust estimators of serial dependence, this work contributes to a more nuanced interpretation of emerging early-warning signals reported in recent literature. The results indicate that multiple independent indicators consistently point toward a long-term destabilization of the AMOC, although substantial uncertainty remains regarding the timing and magnitude of potential transitions. The study underscores the importance of combining physically informed climate understanding with statistically robust monitoring frameworks to improve early detection of large-scale climate tipping dynamics. These findings are relevant for climate risk assessment and for refining observational strategies aimed at monitoring critical components of the Earth system.

Keywords: Atlantic Meridional Overturning Circulation, early-warning signals, climate tipping points, spectral analysis, global temperature variability, critical slowing down.

INTRODUCTION

The stability of the Atlantic Meridional Overturning Circulation (AMOC) is widely recognized as a cornerstone of the Earth's climate system. By transporting warm surface waters northward and returning colder, denser waters southward at depth, the AMOC plays a decisive role in regulating hemispheric temperature gradients and regional climate patterns across the North Atlantic and adjacent continents [4,11]. Paleoclimate evidence and numerical modeling studies suggest that the AMOC exhibits nonlinear behavior and may possess multiple quasi-stable states, raising concerns about the possibility of abrupt transitions under sustained external forcing.

In recent decades, observational records have increasingly indicated a long-term weakening of the AMOC, inferred

indirectly through surface temperature patterns, salinity anomalies, and ocean circulation proxies [1,4,11]. These developments have intensified scientific interest in identifying early-warning signals that could precede a critical transition. Such signals are typically associated with the phenomenon of critical slowing down, whereby a system's recovery rate from perturbations diminishes as it approaches a bifurcation point. Observable statistical manifestations include increasing variance, rising autocorrelation, and enhanced low-frequency variability in relevant time series [1,5].

The detection of early-warning signals in climate systems poses substantial methodological challenges. Climate time series are characterized by strong trends, seasonal cycles, non-Gaussian noise, and time-varying variance, all of which complicate the estimation of statistical indicators.

Furthermore, observational records are relatively short compared to the intrinsic timescales of ocean circulation, necessitating careful treatment of uncertainty and robustness [8,9]. Recent contributions have highlighted the need for improved statistical estimators that remain reliable under heteroscedasticity and non-stationarity [12–15].

This study aims to provide a comprehensive, observation-based assessment of early-warning signals of AMOC instability, integrating insights from climate dynamics, statistical time-series analysis, and spectral estimation theory. By synthesizing global temperature datasets with advanced analytical tools, the work seeks to clarify the evidentiary basis for claims of an approaching AMOC tipping point while explicitly acknowledging methodological limitations. In doing so, the article contributes to the broader discourse on climate tipping dynamics and the role of statistical monitoring in Earth system science.

METHODS

Data Sources and Climate Indicators

The analysis relies on global and regional surface temperature datasets that have been widely used in climate monitoring. Primary attention is given to the GISS Surface Temperature Analysis (GISTEMP, version 4) [6,8] and the HadCRUT5 dataset [9], both of which provide long-term reconstructions of near-surface temperature anomalies from the mid-nineteenth century to the present. These datasets are selected due to their extensive spatial coverage, transparent uncertainty treatment, and frequent use in AMOC-related studies [1,5].

Temperature anomalies are considered both at the global scale and within the North Atlantic region, where AMOC-related fingerprints are most pronounced. Regional averaging is performed following established approaches that emphasize subpolar North Atlantic variability, which has been shown to correlate with AMOC strength [4,11]. To minimize spurious effects from data gaps and measurement changes, the analysis adheres to the uncertainty models provided by the dataset developers [8,9].

Statistical Indicators of Early-Warning Signals

Early-warning theory predicts that systems approaching a critical transition exhibit specific statistical patterns, including increasing variance and autocorrelation at short lags [1,5]. These indicators are computed using rolling windows to track their temporal evolution. Care is taken to remove long-term trends prior to analysis, as trends can artificially inflate variance and autocorrelation estimates.

Autocorrelation is estimated using heteroscedasticity-robust methods that account for time-varying variance in climate

data [14]. These estimators are based on transformations that reduce sensitivity to extreme values and non-Gaussian noise, thereby providing more reliable inference under realistic climate conditions [12,13]. The use of robust estimators is particularly important when analyzing temperature records affected by episodic volcanic forcing and seasonal variability.

Spectral Analysis and Maximum Entropy Methods

In addition to time-domain indicators, frequency-domain analysis offers complementary insights into system dynamics. An increase in low-frequency spectral power is expected as recovery times lengthen near a critical threshold [2,3]. Maximum entropy spectral analysis (MESA) is employed to estimate power spectra with high resolution, even for relatively short time series [2].

The MESA approach is well suited to climate applications because it does not impose strong assumptions about the underlying spectral shape and can resolve subtle changes in low-frequency variability [3]. Spectral estimates are computed for successive segments of the temperature record to examine temporal changes in dominant frequencies and spectral slopes. These results are interpreted in conjunction with time-domain indicators to assess consistency across methodological perspectives.

Treatment of Seasonality and Non-Stationarity

Seasonal effects and long-term warming trends present significant challenges for early-warning detection. Seasonal cycles are removed using standard climatological averaging, while residual seasonality is addressed through variance stabilization techniques [15]. Non-stationarity associated with anthropogenic forcing is handled by detrending using low-order polynomial fits and by comparing results across alternative detrending methods to assess robustness.

All statistical analyses are conducted using the R statistical environment [10], which provides a flexible platform for implementing custom estimators and reproducible workflows. Sensitivity analyses are performed to evaluate the dependence of results on window length, detrending choices, and estimator selection.

RESULTS

Temporal Evolution of Variance and Autocorrelation

The analysis reveals a gradual increase in variance in North Atlantic temperature anomalies over the twentieth and early twenty-first centuries. This pattern is observed across both GISTEMP and HadCRUT5 datasets, suggesting

that it is not an artifact of a particular reconstruction method [6,9]. The increase in variance is more pronounced in subpolar regions, consistent with prior studies linking this area to AMOC dynamics [4,11].

Autocorrelation at lag-1 exhibits a similar upward tendency, particularly after the mid-twentieth century. Robust estimators yield more conservative values than conventional methods, yet the overall trend remains evident. These findings align with theoretical expectations of critical slowing down and with recent observational analyses [1,5].

Spectral Signatures of Low-Frequency Variability

Maximum entropy spectral analysis indicates a progressive enhancement of low-frequency power in North Atlantic temperature records. Spectral peaks shift toward longer periods, implying a lengthening of dominant timescales. This behavior is consistent with a reduction in the system's ability to recover from perturbations and supports interpretations based on time-domain indicators [2,3].

Comparisons between early and late segments of the record suggest that the spectral slope at low frequencies has become steeper, further indicating increased persistence. While uncertainties remain substantial, particularly at the longest timescales, the convergence of spectral and autocorrelation evidence strengthens the case for emerging early-warning signals.

Consistency across Datasets and Methods

A key result of this study is the consistency of trends across independent datasets and analytical approaches. Although absolute indicator values differ depending on methodological choices, the direction of change remains robust. This convergence reduces the likelihood that observed patterns arise solely from data artifacts or methodological bias.

Nevertheless, the magnitude of estimated changes varies, underscoring the importance of uncertainty quantification. Confidence intervals derived from resampling methods indicate that while trends are statistically distinguishable from zero, they are subject to wide uncertainty bounds, particularly in earlier periods with sparse observations [8,9].

DISCUSSION

Interpretation in the Context of AMOC Dynamics

The observed increase in variance, autocorrelation, and low-frequency spectral power is consistent with theoretical expectations for a system approaching a critical transition. In the context of AMOC dynamics, these patterns may reflect a gradual loss of stability associated with freshwater forcing, polar amplification, and changes in deep-water formation

[7,11].

However, it is essential to emphasize that early-warning signals do not imply inevitability or precise timing of a transition. Rather, they indicate reduced resilience and heightened sensitivity to perturbations. The AMOC is influenced by a multitude of interacting processes, and observational indicators capture only a subset of these dynamics [4,17].

Methodological Strengths and Limitations

The integration of robust statistical estimators and spectral methods represents a methodological advancement over earlier studies that relied on simpler indicators. By explicitly addressing heteroscedasticity and non-stationarity, the analysis reduces the risk of spurious detections [14,15].

Nonetheless, limitations remain. Detrending choices can influence results, and separating internally generated variability from externally forced trends is inherently challenging. Moreover, the relatively short length of high-quality observational records limits the ability to detect slow processes with high confidence [1,5].

Implications for Climate Monitoring and Risk Assessment

The findings underscore the value of sustained observational monitoring and methodological refinement. Early-warning indicators should be viewed as components of a broader diagnostic framework that includes physical observations, model simulations, and process-based understanding. Such an integrated approach is essential for informing climate risk assessment and adaptation planning.

Future research would benefit from combining surface temperature indicators with direct oceanographic measurements, such as those provided by mooring arrays and autonomous platforms [17]. Advances in statistical methodology, particularly in the treatment of non-stationary and multivariate data, are also likely to enhance early-warning detection capabilities.

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