

Climate network characterization of the Atlantic Meridional Overturning Circulation edge state

Laure Moinat^{1,2}, Reyk Börner³, Valerio Lucarini^{4,5}, Maura Brunetti^{1,2} and Henk A. Dijkstra³

¹Group of Applied Physics and Institute for Environmental Sciences, *University of Geneva*, Geneva, Switzerland

²Centre pour la Vie dans l'Univers (CVU), *University of Geneva*, Geneva, Switzerland

³Institute for Marine and Atmospheric Research Utrecht, Department of Physics, *Utrecht University*, Utrecht, The Netherlands

⁴School of Computing and Mathematical Sciences, *University of Leicester*, Leicester, United Kingdom

⁵School of Sciences, *Great Bay University*, Dongguan, People's Republic of China



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The Atlantic Meridional Overturning Circulation (AMOC) has been identified as a tipping element in the Earth system. Under the current climate change scenarios, it is urgent to develop robust methods for determining the probability of future AMOC transitions. Recent studies using an Earth system model of intermediate complexity (EMIC) have revealed the importance of an AMOC edge state, located on the boundary of the attraction basin of the collapsed state, in AMOC transitions. Here, we provide a characterization of this edge state through climate networks, using instantaneous temporal correlations between geographical locations to define the network links. We apply the climate network analysis to a set of EMIC simulations with CO₂ forcing according to an intermediate climate change scenario (SSP2-4.5), which exhibit qualitatively different AMOC responses as a result of interaction with the edge state. We show that network measures, specifically the normalized degree centrality, reveal the presence of teleconnections across the equator as the AMOC approaches the edge state. A similar result is obtained for an Earth system model (ESM) simulating AMOC collapse or recovery, suggesting that climate networks could be used to detect an AMOC instability in ESMs and observations.

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I. INTRODUCTION

The current climate crisis raises concerns about crossing critical thresholds of tipping elements in the Earth system [1]. One of them, the Atlantic Meridional Overturning Circulation (AMOC), has been shown to play a key role in regulating the interaction between tipping elements, through its response to increased warming and freshwater input to the North Atlantic, and its impact on the heat and water cycles at the global scale [2,3]. There are observational indications that the AMOC may have weakened over the past 50 years [4–6], in addition to early warning signals of a potential collapse [7]. Moreover, climate models of different complexity have been used to investigate the effect of CO₂ ramping rates and freshwater hosing on the AMOC strength, showing that the AMOC can be destabilized on a centennial timescale (e.g., [8–10]). In state-of-the-art Earth system models, a transition to extremely weak overturning can occur in high-emission scenarios but also sometimes in intermediate- and low-emission scenarios [11–13]. Yet, many simulations also show an AMOC recovery following a transient weakening, raising the question of how to distinguish a forced transient response from the onset of an AMOC tipping event (transition to a weak or collapsed state).

This calls for robust metrics on decadal timescales for AMOC destabilization.

As deduced from the behavior of box models [14–18] and more complex models [19–25], a bistable regime may exist with an ON state, which corresponds to the current state of the AMOC, and an OFF state with a weak or collapsed EDGE (or melancholia) state [26] lies on the basin boundary separating the two basins of attraction, represented by the unstable branch in a bifurcation diagram. Although edge states are unstable, they can govern the transient dynamics of the system in considerable regions of phase space, especially when acting as gateways for transitions between competing attracting states. However, reaching an edge state does not necessarily imply a tipping event, since its repelling forces point away from the basin boundary on either side. Whether the system tips or not ultimately depends on the initial condition as well as the external forcing protocol (in the deterministic context considered here).

Edge states of the climate system have been identified in a conceptual climate model composed of a chaotic atmosphere coupled to the bistable Stommel ocean [27], a simplified atmosphere model coupled to an ocean energy balance model (PuMA-GS) [26], an ocean-only general circulation model (GCM) [28], and in PlaSim-LSG, an Earth system model of intermediate complexity (EMIC) [10]. In PlaSim-LSG, the AMOC edge state is characterized by large AMOC oscillations with a characteristic centennial timescale, mainly

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driven by the alternating weak and strong convective regimes in the Labrador Sea [10].

The so-called edge tracking algorithm [29,30] is the main tool for identifying an edge state in such models [10,26]. This algorithm consists of an iterative bisection procedure that is aimed at nudging the system toward following a forward trajectory along the boundary separating the competing basins of attraction. Eventually, the system settles on the edge state, which attracts the trajectories initialized on the basin boundary. In box models and an ocean-only GCM, observables exhibiting an increase in fluctuations when approaching a tipping point have been shown to be directed toward the edge state in state space [31]. This property could be used to identify the relevant variables showing substantial critical slowing down in a high-dimensional system [31], thus revealing the potential role of the edge state in informing early warning signals of an AMOC instability.

Applying the edge tracking algorithm to comprehensive Earth system models (ESMs) is not feasible at the moment due to computational limitations. Therefore, we propose an alternative way to infer the edge state using climate networks, which combine both spatial and temporal information of dynamical processes [32]. Climate networks have been successfully used to identify linear and nonlinear properties of the climate system [33–35], to describe teleconnections [36], to investigate the dynamics of climate subsystems as the AMOC [37] and El Niño-Southern Oscillation [38], or global-scale tipping [39], and as a mathematical tool to identify properties that cannot be directly inferred from time series analyses [33]. Climate network analysis has been used to determine early warning signals of an AMOC collapse in the FAMOUS model [23,40], with the kurtosis of the degree distribution as main indicator.

From a dynamical systems point of view, the onset of an AMOC collapse may be defined as the trajectory exiting the (forcing-dependent) basin of attraction of the AMOC-ON state by crossing its basin boundary. Furthermore, the AMOC-ON state may lose stability by colliding with the edge state in a so-called boundary crisis at a critical forcing threshold [10]. Instead, if (sufficiently weak) stochastic forcing is present in the system, the edge state acts as the most probable gateway for noise-induced transitions [41,42]. This highlights the central role of the edge state for AMOC tipping. While transitions under transient forcing are not guaranteed to travel through the edge state, they are likely to interact with its dynamics, especially under near-critical forcing. The recovery of the AMOC following a substantial excursion toward the OFF state can also be associated with a close approach of the edge state with avoided tipping. Hence, we expect to be able to identify the edge state's spatial signature in climate model simulations under different emission scenarios where the AMOC shows collapse or recovery.

The paper is organized as follows. First, we briefly describe the climate model simulations used in the present study, how we construct the climate networks [34], and the network indicators used to perform the analysis. Next, to identify relevant observables, we compare the climate network constructed from simulations under preindustrial conditions against that constructed from reanalysis data. Using these observables, we construct and characterize the climate

networks of the simulated ON, OFF, and EDGE states. We also investigate the temporal evolution of network indicators for an initial condition ensemble of AMOC trajectories that intersect with the EDGE state under an intermediate CO₂ emission scenario. Finally, we apply the same network analysis to simulations obtained under a similar forcing scenario with the NASA GISS model [11], an ESM participating in the Coupled Model Intercomparison Project (CMIP) phase 6. These simulations have attracted considerable interest because different members of the same ensemble showed qualitatively different responses to the same protocol of forcing, with some members showing a modest response of the AMOC, while others featured a long-lived substantial reduction of its strength [11]. This behavior has been interpreted as the outcome of a possible boundary crisis where an edge state collides with the AMOC ON state [10].

II. METHODS

A. Climate model simulations

The present analysis is based on the results of the climate simulations described in Ref. [10], obtained using PlaSim-LSG [43]. For preindustrial forcing conditions where the CO₂ concentration is set to 285 ppm, three equilibrium states of the AMOC were identified: ON, OFF, and EDGE states. The ON state corresponds to the preindustrial AMOC, the OFF state shows a weakened AMOC with a shutdown of North Atlantic deep convection, and the EDGE state has an intermediate AMOC strength with centennial-scale oscillations.

These three states were also obtained at present-day forcing conditions (360 ppm), and we will use the simulations at 360 ppm to explicitly characterize the EDGE state behavior because they provide longer time series than at 285 ppm (see Ref. [10]). Starting from the ON state at 285 ppm, further transient PlaSim-LSG simulations were performed, imposing the increase in CO₂ of the shared socioeconomic pathway (SSP) 2-4.5 [44], an intermediate emission scenario, for five ensemble members until the year 2500 [10].

In addition, we use data from several simulations with the NASA GISS-E2-1-G model [11] that have been highlighted in the qualitative comparison between the GISS and PlaSim-LSG models performed in Ref. [10]. In the GISS model, the ocean has a resolution of $1^\circ \times 1.25^\circ$ with 40 vertical levels and was regridded to a resolution of $2^\circ \times 2^\circ$ to limit the computational time required by the network analysis. The three extracted ensemble members are r1i1p1f2, r7i1p1f2, and r10i1p1f2 for the SSP2-4.5 scenario, with their corresponding historical data. The piControl simulation from r1i1p1f2 is used as the ON state reference for the three ensembles, since it is the only one available. In all the transient simulations for PlaSim-LSG and NASA-GISS, the climate networks are performed with a moving time window of 25 (Appendix) or 50 years (main text).

In order to determine the most appropriate observables for the network construction, the ORA20C reanalysis (which combines a ten-member ensemble of reanalyses) [45] is used. In ORA20C, the 1900–1925 period with an annual resolution is taken; hence, we obtain a time series of 25 years. ORA20C

has a resolution of $1^\circ \times 1^\circ$ and was regridded to fit the PlaSim-LSG resolution of around $3.5^\circ \times 3.5^\circ$.

B. Climate networks

Climate networks are statistical tools to unveil the structure of interactions (links or connections) between subsystems (nodes or vertices) of a complex system. Here, the set of links L between pairs of nodes (p, q) is defined depending on the degree of statistical interdependence between the corresponding pairs of annual-mean time series at the grid points of climate model output [34]. The links between nodes in an undirected network are represented by a symmetric matrix A , called the *adjacency matrix* [46]:

$$A_{pq} = \begin{cases} 0, & \text{if } (p, q) \notin L, \\ 1, & \text{if } (p, q) \in L. \end{cases} \quad (1)$$

For a network containing N nodes, the size of the adjacency matrix is $N \times N$ [32].

In this work, the Pearson correlation coefficient (PCC) is used to generate the complex network. PCC measures the similarity of two time series X , Y and is defined as

$$\rho_{X,Y}(\tau) = \frac{\text{cov}(X(t), Y(t + \tau))}{\sqrt{\sigma_X^2 \sigma_Y^2}}, \quad (2)$$

where σ_X^2 and σ_Y^2 are the variances of the variables X and Y , respectively, and $\text{cov}(X(t), Y(t + \tau))$ is the covariance of the two time series as a function of the time lag τ . In this work, we set $\tau = 0$, so that $\rho_{X,Y}(0)$ becomes symmetric, $\rho_{X,Y}(0) = \rho_{Y,X}(0)$, and bounded between -1 and 1 [32].

The resulting undirected and area-weighted climate networks are computed using the PYUNICORN package [34], and links are generated at a fixed threshold of 0.5, using the *climate.TsonisClimateNetwork* function. This means that links between two time series at different grid points are established if the correlation coefficient is larger than 0.5. This threshold has been chosen to avoid the saturation effect that occurs when the threshold is too small and, at the same time, to guarantee a sufficient number of links, as shown in Ref. [39]. To generate the networks, a window size of 25 or 50 years is used for several reasons: sufficiently long time series are needed to generate statistically robust networks; the limited length of observational data; and the duration of strong and weak phases of the EDGE-state oscillations.

Correlations at zero lag capture how ocean variables covary instantaneously (i.e., on annual timescales) at different locations. Long-range interactions must therefore be mediated by relatively fast processes, e.g., atmospheric teleconnections. This is different from considering the advective transport of mass, energy, and information between regions on longer timescales.

Our network analysis is based on the adjacency matrix and two global network measures, namely, the normalized degree (ND) centrality and the average length distance (ALD), since they have been identified as relevant indicators when looking at global-scale tipping behavior [39]. The normalized degree centrality at node v , ND_v , is defined in terms of the adjacency

matrix [47]:

$$\text{ND}_v = \frac{1}{N} \sum_{i=1}^N A_{vi}. \quad (3)$$

This indicator is bounded between 0 and 1 and gives the proportion of correlated sites per node. In the analysis, the average is calculated to obtain the mean value across the network.

The second indicator is the ALD, which corresponds to the topological distance (defined as positive) between pairs of nodes:

$$\text{ALD} = \frac{1}{\binom{N}{2}} \sum_{i < j} d_{ij}, \quad (4)$$

where d_{ij} is the minimum number of links that need to be crossed to travel from node i to node j and $\binom{a}{b}$ denotes the binomial coefficient. Disconnected pairs are not included.

The adjacency matrix and the ND and ALD indicators are used to extract information about the AMOC states. A large average ND across the network indicates a relatively high degree of spatial correlation throughout the system, with a similar pattern for the ALD. In order to evaluate the number of links between two regions, we extract from the adjacency matrix the vertices in the corresponding regions. Then, the density of connections is given by the ratio between the links of one region to the other and the total number of possible links between these two regions. Noise is excluded by setting a threshold at 5% in the connection density.

C. Fields and observables

To construct the network, we consider two ocean fields that characterize the AMOC state: temperature and salinity. These have been found to be strongly coupled through advection and water mass formation and have been identified as key variables for the AMOC stability since the seminal work of Stommel [14] and across a range of models [9].

As this study focuses on the AMOC behavior, we apply the climate network on the North Atlantic basin and selected subregions to better understand the potential teleconnections between them. Based on previous works, we consider four relevant regions (Fig. 1): the Labrador Sea, the North-East Atlantic, the Arctic Ocean, and the southern border of the Atlantic (the 34°S corridor). The first two regions are associated with the main convective sites in PlaSim-LSG simulations, and the Arctic Ocean plays an important role in the EDGE-state behavior [10] and centennial AMOC variability [48]. The 34°S corridor connects the Atlantic Ocean with the other ocean basins and plays a key role in the salt-advection feedback [7,23,49].

To assess the robustness of the network structure, we have evaluated its performance against reanalysis data. Thus, the climate networks generated from the PlaSim-LSG ON state (the preindustrial PlaSim-LSG simulation at 285 ppm) are compared with those from the ORA20C reanalysis in the 1900–1925 period, more precisely by comparing region-to-region connections.

For the ON state in PlaSim-LSG, the entire simulated period is considered and cut into chunks of 25 years, which are

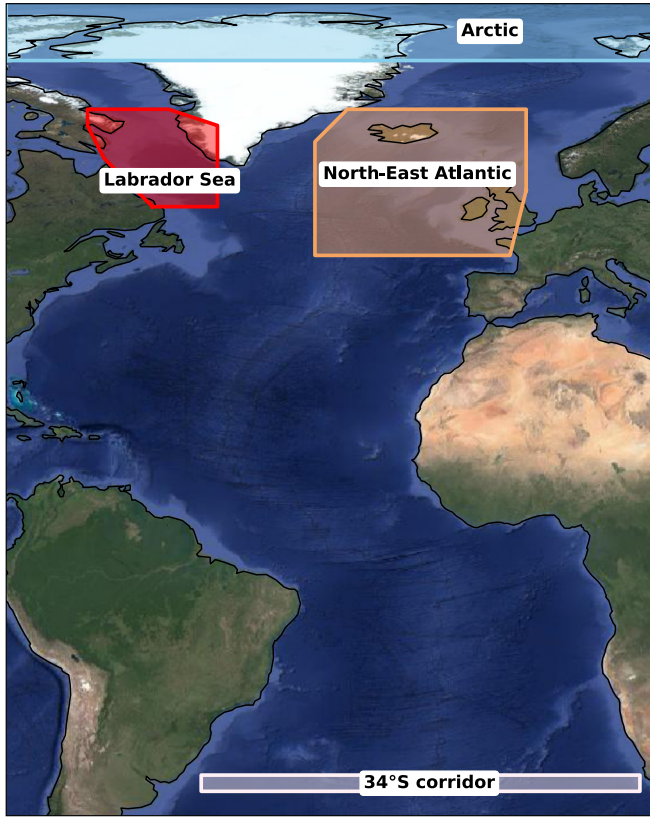


FIG. 1. Regions used to compute the connection density in the climate network. They include the Arctic (light blue), the Labrador Sea (red), the North-East Atlantic (light brown), and the 34°S corridor (light pink).

then averaged, due to the equilibrium nature of this simulation. This evaluation was performed for sea temperature and salinity at the surface (top 50 m) and at depth (average values between 300 and 1000 m). The difference between the raw fields can be seen in Fig. 6.

As shown in Fig. 7, the networks generated using sea surface temperature in PlaSim-LSG and in ORA20C display the same region-to-region connections, namely, between the Labrador Sea and the North-East Atlantic, with a comparable intensity. For the networks constructed from potential temperature at depth, the intensity of the connections in the ON state

is in the 30% range, while that in ORA20C is less than 15%. The Labrador Sea is not directly connected to the 34° corridor in ORA20C, while the other region-to-region connections are qualitatively the same in the two cases. Thus, we conclude that the interregional network connections based on the ocean temperature in the PlaSim-LSG ON state at 285 ppm capture the main dynamical features of the network connections in ORA20C. This is not satisfied by the networks constructed using the salinity field, neither at the surface nor at depth. Freshwater biases are a common issue in global climate models [50] and could also cause the discrepancies in the network structure of the salinity field. Additionally, PlaSim-LSG has several important limitations in representing ocean dynamics, including the coarse resolution, Southern Ocean biases, lack of eddy parametrization, and a simplified convective adjustment scheme [43].

III. RESULTS

A. State characterization

We will next use the 360 ppm Plasim-LSG ON state simulation (see Table I). In this case, the ON state acts as the reference for the network behavior. As with the ON state at 285 ppm, at the surface there are weak connections between the Labrador Sea and the North-East Atlantic, and additional weak connections between the Labrador Sea and the Arctic region (Figs. 2 and 6). This could be related to the retreat of the sea ice extent in the Arctic region under warming conditions, possibly enabling atmospheric teleconnections to the Labrador Sea. At depth, we see the appearance of the connections of the 34°S corridor with the Arctic region, the North-East Atlantic, and the Labrador Sea, as in the 285 ppm case.

The OFF state displays a network structure that is different from the ON state. At the surface, only the Labrador Sea and the North-East Atlantic are connected, while the Arctic region does not connect with these two regions. In this case, the Arctic region is fully covered by sea ice [10], since, because of the presence of a weak AMOC, the sea ice has expanded southward. As a result, the surface Arctic Ocean may be effectively decoupled even from the neighboring regions. At depth, there is an overall decrease in intensity of the connections between the northern and southern hemispheres, while the coupling increases within the northern hemisphere.

TABLE I. Datasets and climate model characteristics for the different experimental configurations. For the GISS model, the ensemble members are reported explicitly. For the piControl, the simulation length is 1000 years.

	PlaSim-LSG	ORA20C	NASA-GISS-E2-1-G	Analysis
Resolution	$3.5^\circ \times 3.5^\circ$	$3.5^\circ \times 3.5^\circ$	$2^\circ \times 2^\circ$	NA
Window size (yr)	25, 50	25	50	NA
piControl	285 ppm	1900–1925	r1i1p1f2	Observable selection
Present day	360 ppm	NA	NA	State characterization
SSP2-4.5	5 members	NA	r1i1p1f2, r1i1p1f10, r1i1p1f7	Network indicators

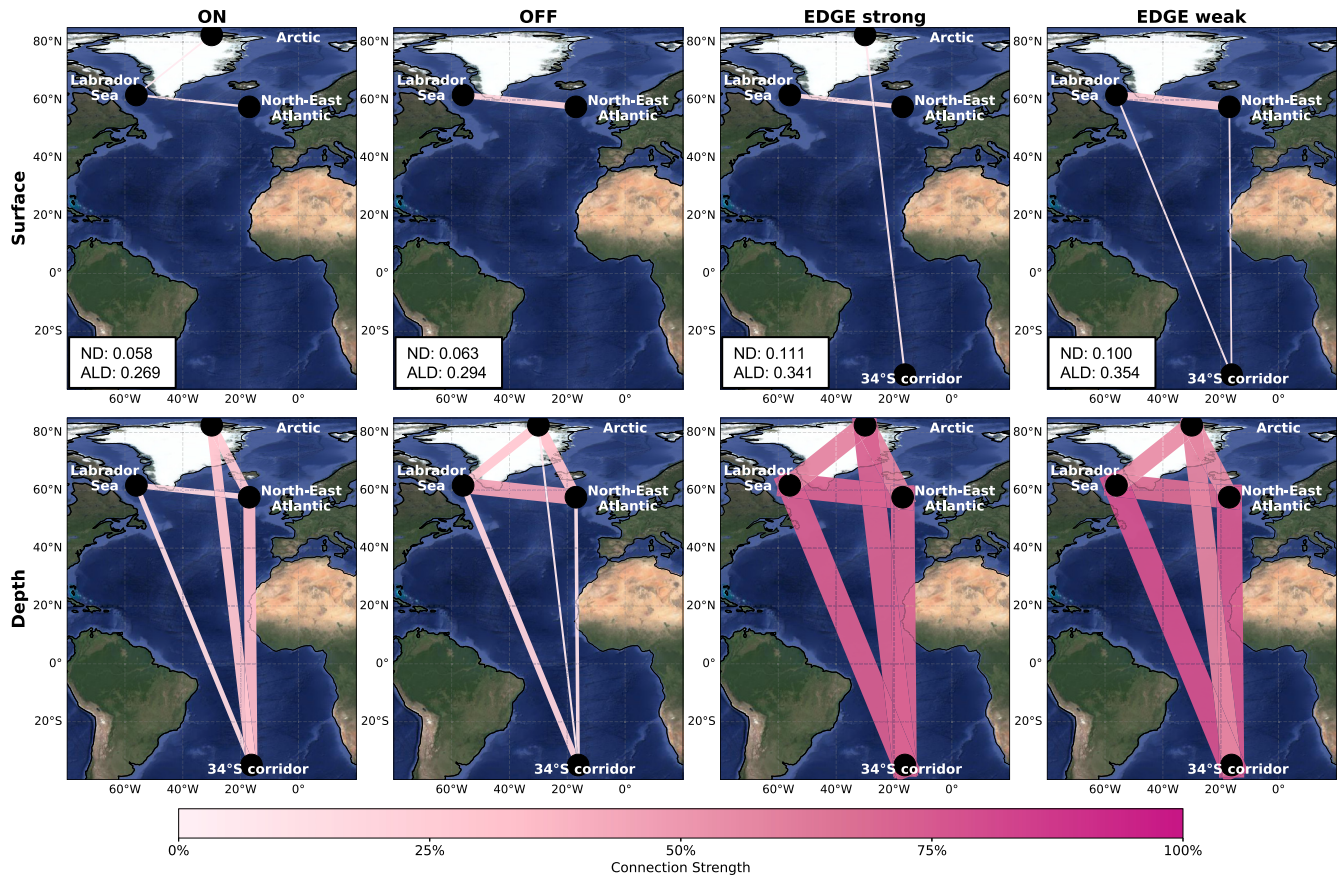


FIG. 2. Region-to-region connections for the ON (first column), OFF (second column), EDGE strong (third column), and weak (fourth column) states at the surface (first line) and at depth (second line) obtained under the 360 ppm CO_2 value, where “weak” and “strong” refer to the convection intensity in the Labrador Sea. For the surface, the average values of the ND centrality and the ALD of the Atlantic basin are also shown in the inset. The darkness of the pink color and the thickness of the connecting lines are proportional to the connection density. A 5% threshold has been applied to remove the noise. The region labels are the ones displaying connections with other regions.

This can be linked to the collapsed overturning north of 50°N and associated shutdown of deep convection, likely affecting the connectivity of the overturning circulation across latitudes.

Regarding the EDGE state, the networks have been computed separately for the weak (A) and strong (C) phases of the oscillation identified in Ref. [10], corresponding to weak and strong convection in the Labrador Sea, respectively (Fig. 3).

At the surface, we see that teleconnections with the 34°S corridor appear for both weak and strong convection regimes, hence unveiling that, in the unstable EDGE state, teleconnections occur across the equator. At depth, the connections among all regions are substantially intensified as compared to the ON and OFF states. These connections occurring on decadal timescales between the northern and southern hemispheres have been seen in simpler models, where following a perturbation both hemispheres react coherently and change together [16,17,51]. They are also consistent with the complex network analysis of an AMOC collapse in the FAMOUS model, where high-degree nodes appear near the transition over the whole depth [40].

The salinity and temperature fields during the weak and strong convective regimes of the EDGE state are shown in

Fig. 8. In both convection regimes, the subpolar North Atlantic surface ocean is cooler and fresher compared to the ON state, as less heat and salt is advected from the tropics, while at the same time a slightly warmer and saltier region emerges at the 34°S corridor, in particular, on the western boundary of the South Atlantic Ocean. At depth, the subtropical and tropical Atlantic is substantially warmer compared to the ON state.

To quantify the difference between the strong and weak phases of the EDGE state, we calculated the correlation between the normalized degree centrality in each network, which are $R = 0.19$, $p = 0.002$ for the surface and $R = 0.47$, $p < 0.001$ at depth. For both depths, the correlation coefficient is positive and significant. However, the R value at the surface remains low, emphasizing the need to distinguish between the convective regimes in the EDGE state. This is also seen in the different patterns of region-to-region connections in the North Atlantic basin at the surface (Fig. 2).

At the surface and at depth, the EDGE state has a characteristic network signature, with significantly more connections with respect to the ON and OFF states, and the appearance of teleconnections with the southern hemisphere. Indeed, during a tipping process, the number of spatial correlations increases,

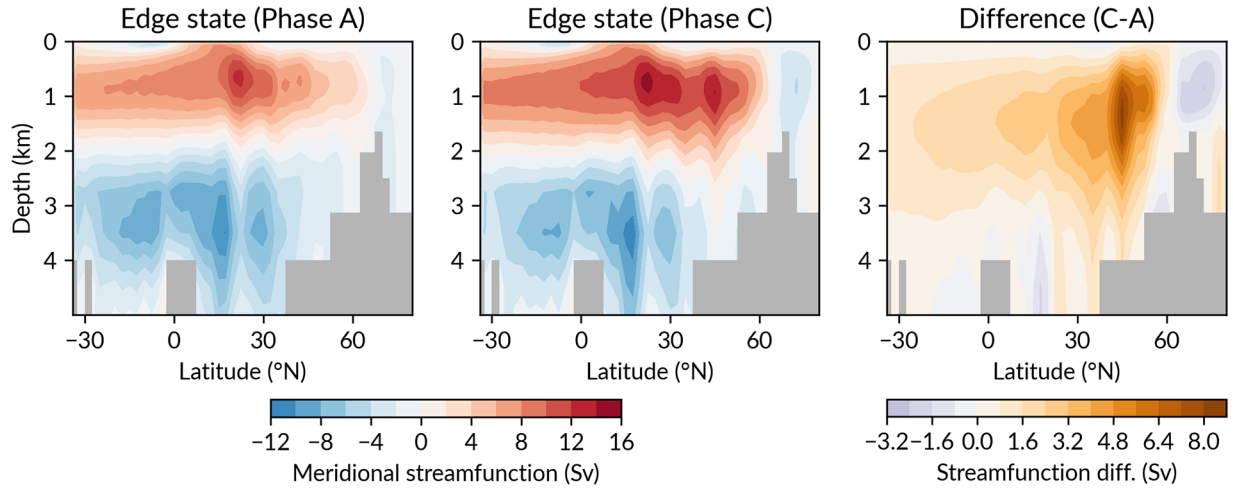


FIG. 3. Overturning streamfunction in the Atlantic basin for the EDGE weak/phase A (first panel), for the EDGE strong/phase C (second panel), and the difference between the EDGE strong and weak (third panel) with the corresponding color scales, where “weak” and “strong” refer to the convection intensity in the Labrador Sea.

similar to what is observed in thermodynamic phase transitions [32]. This behavior can be understood through the so-called slaving principle, according to which, near a bifurcation, all dynamical modes rapidly adjust to the slowly evolving dominant mode, leading to the emergence of spatial correlations that extend across the entire system [32,39,52]. In many networked systems, this is accompanied by critical slowing down and the emergence of synchronization [53,54]. We thus interpret the emergence of interhemispheric teleconnections as a manifestation of a characteristic network signature of an edge state.

B. Proximity to the edge state

We now apply the network analysis to simulations under time-dependent CO_2 forcing representing the SSP2-4.5 scenario. The goal is to use the identified network signature of the EDGE state to detect the approach to the EDGE state in the transient simulations. In certain cases, entering the EDGE-state region does not necessarily imply crossing a tipping point, but remaining near the basin boundary between the ON and OFF states of the AMOC. For the ensemble of PlaSim-LSG simulations, the EDGE state region is defined as the minimal rectangle containing the constructed EDGE state at 285 ppm in the reduced space spanned by the meridional and vertical salinity gradients, as described in Ref. [10]. The entry of a trajectory into this region (Fig. 9), shown by a green vertical line in Figs. 4 and 10, allows us to directly verify the performance of the network indicators for the EDGE-state detection. Note, however, that the EDGE-state region is an approximation since it changes as a function of CO_2 concentration and is based on a finite-time estimation of the edge state, projected onto a low-dimensional latent space of the high-dimensional dynamics.

The AMOC intensity is calculated as the streamfunction maximum in the 46–66°N latitude range (PlaSim-LSG) and the maximum value at 26.5°N below 500 m (GISS), consistent with the conventions in Refs. [10, 11], respectively. Figure 4

displays the evolution of the AMOC intensity (first column), the global ND and ALD (second column), and region-to-region connections of the 34°S corridor with the other three regions defined in Fig. 1, for the five-member ensemble in PlaSim-LSG. All ensemble trajectories lead to the EDGE-state region under the transient forcing, but only four members undergo a subsequent AMOC collapse while one member maintains a relatively strong AMOC.

To evaluate the variability in the ON state, the mean and standard deviation σ are computed for each indicator and each region-to-region connection density. Then, a 3σ band is represented as dashed lines in the different subplots. To compute the network indicator time series, a moving window of 50 years is used. Using a 25-year moving window produces similar but noisier results (Fig. 10). For comparison, we also perform the analysis for temperature at depth (Fig. 11, using again a time window of 50 years), but we focus on the surface in the following since the signal is most clear there.

The 34°S corridor shows intensifying connections to other regions before entry into the EDGE-state region, regardless of whether the eventual fate of the AMOC is collapse or recovery. The global indicators (namely, the normalized degree centrality and the average path length in the second column of Fig. 4) exit the 3σ variability band well before entering the EDGE-state region, suggesting that the system is exploring an unusual dynamical regime. The key point here is that the proximity to the EDGE state (rather than the OFF state) is rather well represented, as can be seen by comparing the results obtained for both the collapsed and recovery AMOC cases; the latter is shown in the third row of Fig. 4. This result provides a new method to unveil the presence of an edge state in complex climate models where it is currently too computationally expensive to explicitly compute it.

The selected GISS simulations comprise one collapsing member, one with late recovery, and one with early recovery (Fig. 5; see also Fig. 14 in Ref. [10]). In the GISS model, the presence and location of an AMOC edge state are not known, but the divergence of ensemble members

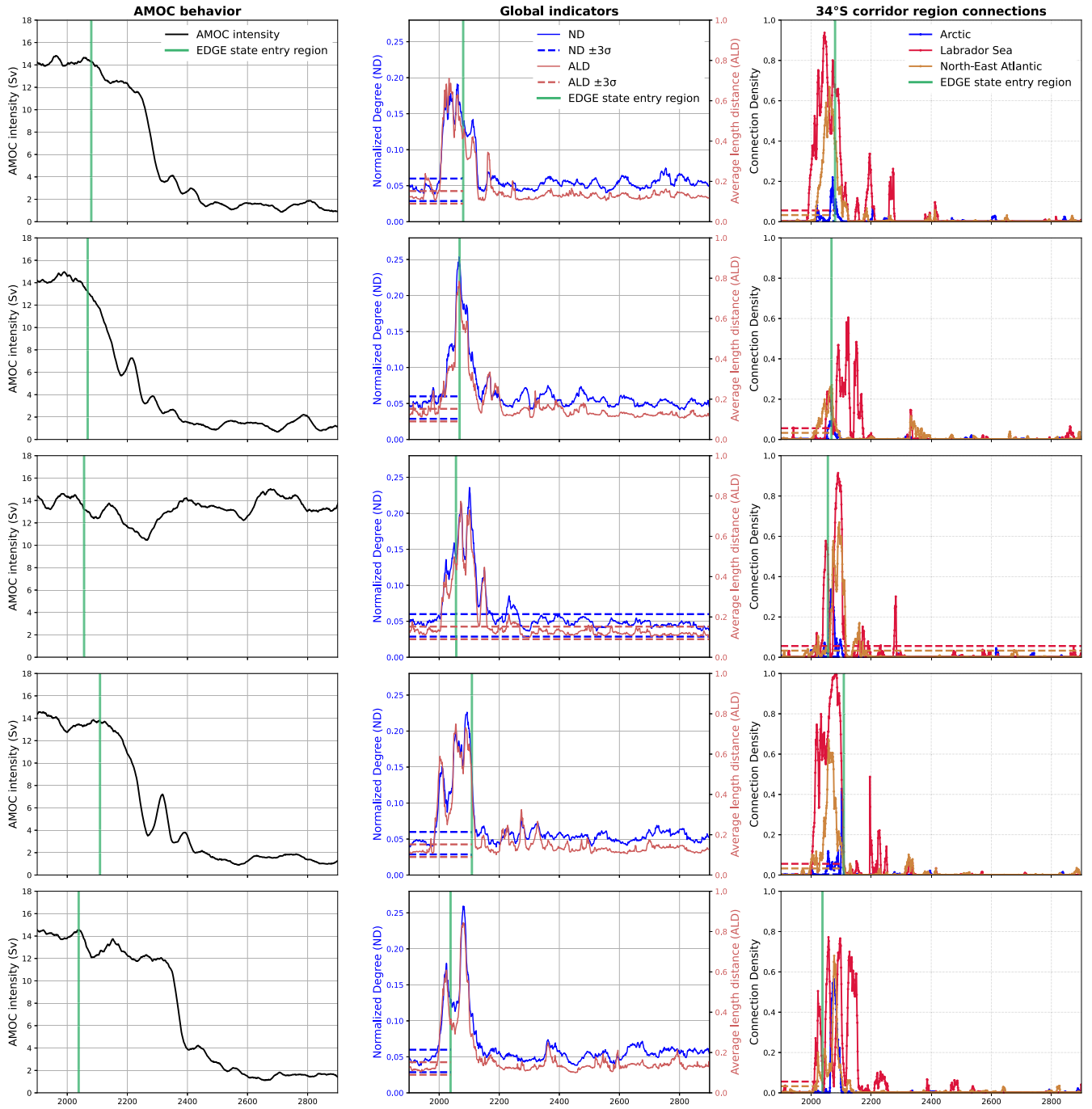


FIG. 4. Temporal evolution of the AMOC intensity (first column), global network indicators (second column), and region-to-region connections starting from the 34°S corridor (third column) in five PlaSim-LSG simulation ensemble members using a 50-year moving window. The two acronyms ND and ALD stand for normalized degree and average length distance. The green vertical line corresponds to the time when the AMOC enters the EDGE-state region, as inferred from the reduced salinity phase space in Ref. [10].

suggests transition through a highly unstable region of the phase space. Furthermore, a qualitative similarity between the PlaSim-LSG and GISS trajectories has been shown [10]. The normalized degree centrality (blue lines in the second-column panels) and the region-to-region connections from the 34°S corridor (third-column panels) are good indicators of AMOC weakening (corresponding to the vertical gray line in the

first-column panels, where the AMOC intensity becomes lower than the 3σ band of AMOC variability in the ON state), both at the surface (Fig. 5) and at depth (Fig. 12), albeit the signal is clearer at the surface. The normalized degree centrality and connections between 34°S corridor and Labrador Sea also seem indicators for the recovery phase (around year 2300 in the central-row panels). In addition, the similar results

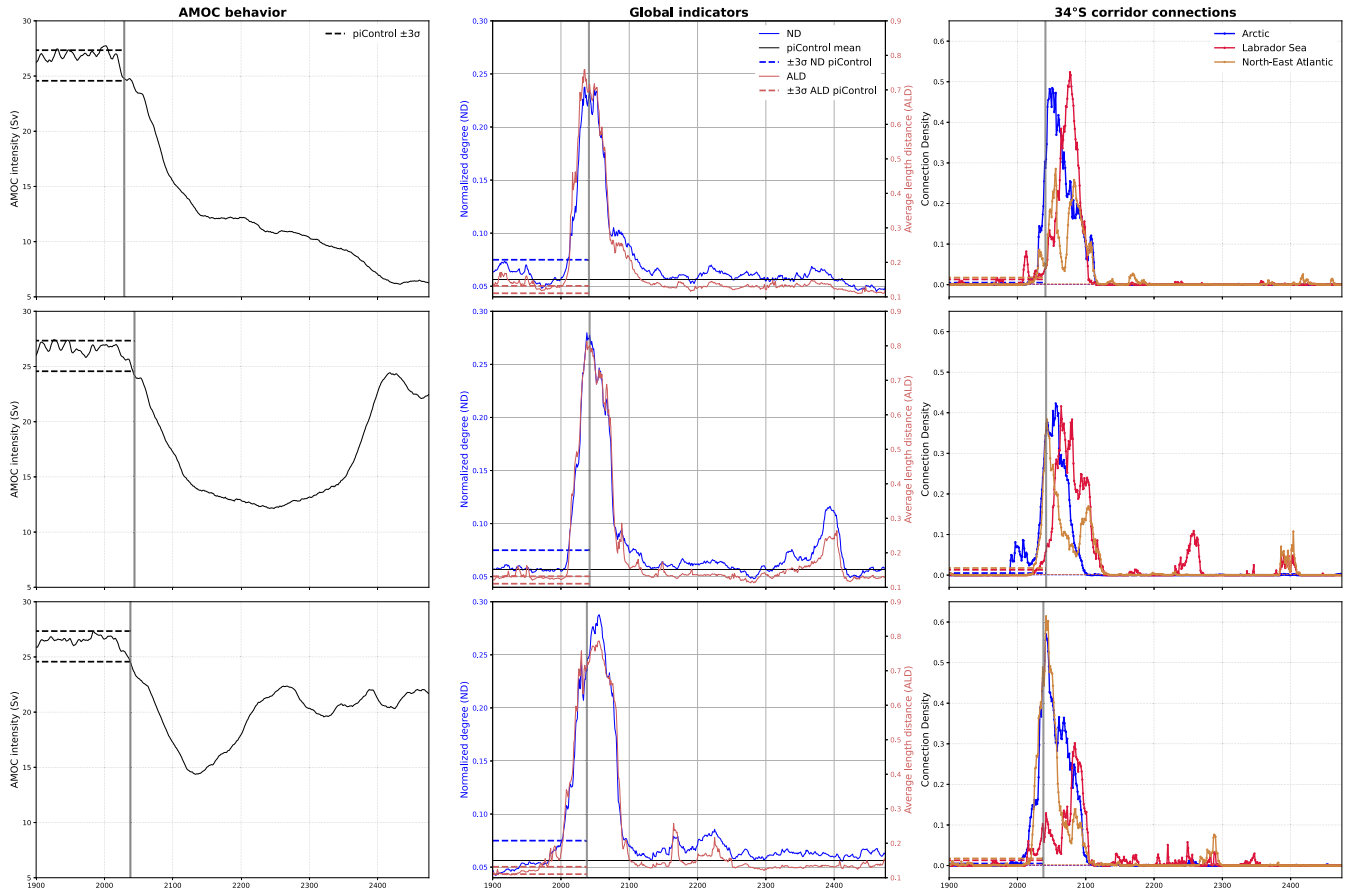


FIG. 5. Same as Fig. 4 in three GISS simulation ensembles (r1i1p1f2, r7i1p1f2, and r10i1p1f2, respectively). The two acronyms ND and ALD stand for normalized degree and average length distance. The gray vertical line corresponds to the time when the AMOC strength exits the 3σ band (dashed lines).

between the PlaSim-LSG and GISS models corroborate the qualitative similarity between the PlaSim-LSG and GISS trajectories identified in Ref. [10], supporting that the GISS model comes close to an edge state.

The network signals obtained from ocean temperature at depth (300–1000 m) have significantly larger background noise than the signals obtained from the surface temperature field (Figs. 11 and 12). Nonetheless, a weaker signal with similarities to the surface signal is visible. When comparing the results at depth between the two models, the signal is clearer in the GISS simulations. This may be related to the difference in the vertical resolution of the models (40 against 22 layers on a stretched vertical grid), leading to a much coarser representation of the mid-depth ocean in PlaSim-LSG.

We note that the relatively pronounced near-surface signal under transient forcing (Figs. 4 and 5) is opposite to the situation under equilibrium conditions, where the network signal is stronger at depth (Fig. 2). This could be due to atmospheric internal variability masking long-range ocean correlations in equilibrium conditions, while under transient forcing the coupled ocean-atmosphere system may respond in a more coherent manner. Another possible explanation is that slow degrees of freedom, such as deep-sea temperature, cannot respond as quickly to the forcing changes, such that

changes in the network structure are more directly apparent in the faster upper-ocean variables. Indeed, forced transitions in multiscale systems may pass through the edge state in fast variables while bypassing it in slow variables [42].

It is important to note that to obtain a clear early warming signal (EWS), several indicators should display a peak above the 3σ band at the same time, while peaks in only one indicator may correspond to false positives. The agreement between the evolution of the normalized degree centrality in the North Atlantic basin and the region-to-region connections provides a coherent picture showing that the system is going away from the ON state, suggesting that all members get close to the basin boundary in the proximity of the edge state. This coherence is also seen at depth (Fig. 12), despite being delayed.

The 34°S corridor teleconnections behave as an important indicator for moving away from the ON attractor and toward the EDGE state in all cases. As identified earlier in the characterization of the states (Fig. 2), the EDGE state is characterized by the appearance of these interhemispheric teleconnections. In all cases, 34°S corridor teleconnections emerge around the year 2000. The signal at depth confirms the peaks in teleconnections for the EDGE state across the equator (Fig. 11). This conclusion can also be applied to the GISS runs, hence emphasizing that the edge-state

behavior does not seem to be unique to PlaSim-LSG. This confirmation by a comprehensive ESM suggests that the network signature could be robust across models of varying complexity.

The order-of-magnitude amplification of interhemispheric teleconnections at the beginning of the 21st century, seen in both the PlaSim-LSG and GISS models, unveils the promising role of spatial correlations in the search for EWSs [55]. Nevertheless, to minimize the number of false positives, several indicators should display the same behavior to have a robust EWS of reaching the AMOC edge state.

IV. CONCLUSION

Understanding the properties of the edge state separating competing stable AMOC states in a multistable regime is key to advancing our knowledge of the AMOC tipping dynamics under transient forcing and toward developing reliable early warning signals. When the AMOC is subjected to destabilizing forcings, such as freshwater flux forcing and/or atmospheric CO₂ increase, the system may come in close proximity to the edge state, regardless of whether the AMOC will subsequently collapse or eventually recover.

The determination of the edge state via edge tracking is computationally challenging and currently still prohibitively expensive in state-of-the-art Earth system models, so it is tempting to try to fingerprint it using reduced-order methods. Since the edge state is an unstable chaotic saddle living on the boundary separating the basins of attraction of the strong and weak AMOC states, it is reasonable to expect that one might identify qualitative differences in its fundamental dynamical properties compared to the stable attractors.

A characteristic signature of the edge state clearly emerges when one constructs climate networks, which provide a reduced representation of both the spatial and temporal dynamics of a complex system. The networks are constructed based on instantaneous (zero-lag) correlations between the annual-mean time series of pairs of model grid points, meaning that they capture how ocean locations covary on annual timescales (rather than advective timescales). The AMOC edge state has a distinct spatial correlation pattern in the horizontal ocean temperature field at the surface and at depth, characterized by strongly enhanced teleconnections within the North Atlantic as well as emergent teleconnections with the South Atlantic. These teleconnections with the southern hemisphere also occur in the 21st century under the SSP2-4.5 scenario in both the PlaSim-LSG and GISS models. In PlaSim-LSG, the trajectories are known to reach the region of the chaotic edge state. The fact that a very similar network signal is detected in the transient simulations in the more complex GISS model strengthens the hypothesis that

the GISS trajectories also interact with an edge state. This provides a dynamical explanation of the ensemble splitting observed in PlaSim-LSG [10], GISS [11], and other models [13]. In addition, the coherent signal obtained by the three network indicators (the normalized degree centrality, the average length distance, and the connections with the 34°S corridor region) for the edge-state detection in both models creates potential for the development of new EWS methods.

The network-based analysis presented here can be carried out on CMIP6 models showing an AMOC weakening or collapse to investigate whether an edge state is approached. This will provide further insight into the robustness of the network signal, also with respect to different observables besides sea temperature. Future developments include assessing the performance of this spatial signature of the edge state in climate networks to serve as an early warning signal of AMOC destabilization. Further work could also explore the physical mechanisms underlying the correlation patterns captured by the network analysis.

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DATA AVAILABILITY

The code used for the network analysis and to produce figures can be found on Zenodo [56]. PlaSim-LSG simulation output by Ref. [10] is archived on Zenodo [57,58]. Due to the large amount of data, the adjacency matrix of the climate networks and additional data can be requested on demand from L.M.

APPENDIX

Additional figures, mentioned in the main text, are shown in this Appendix.

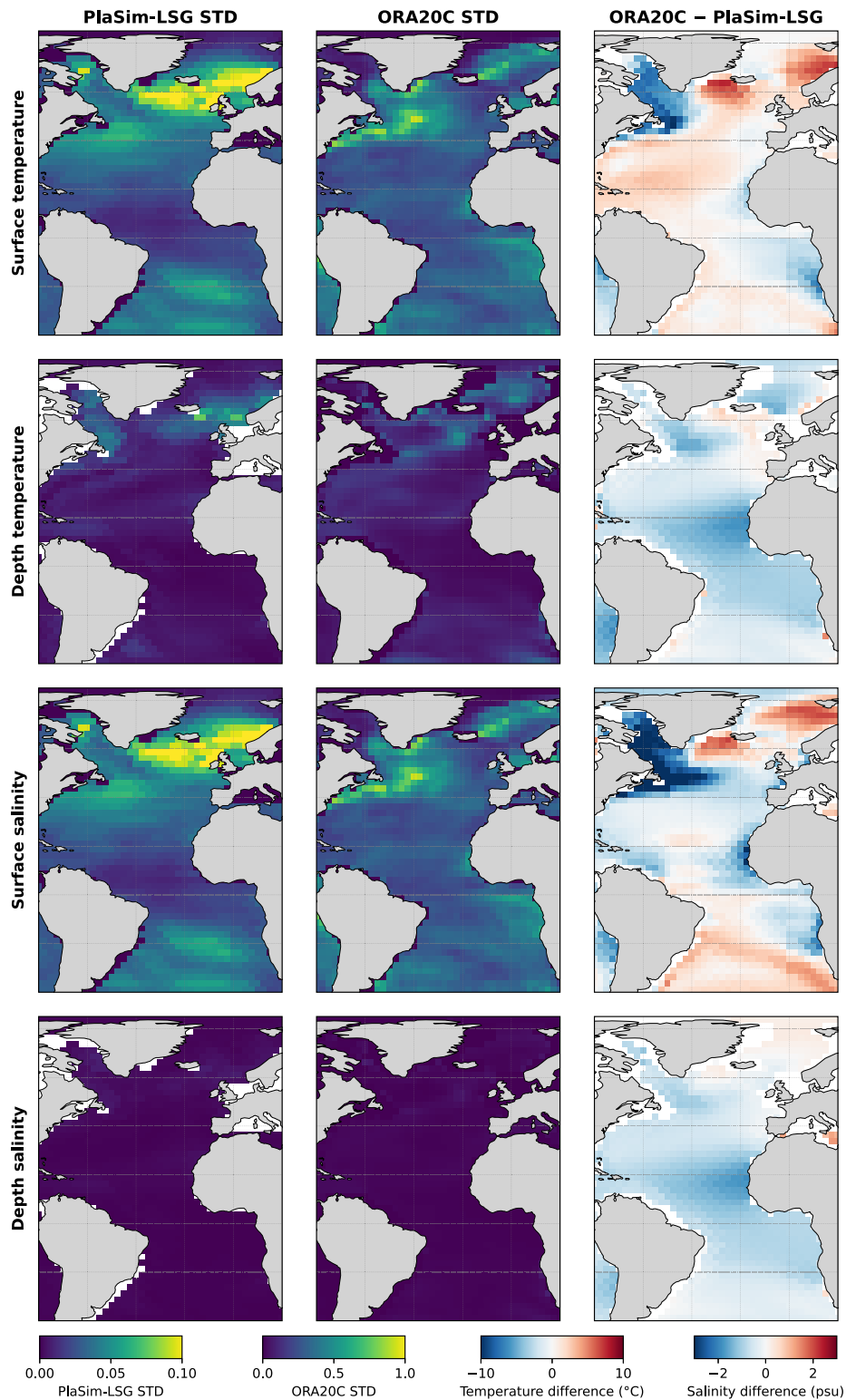


FIG. 6. Raw-field standard deviation (STD) for PlaSim-LSG (first column), ORA20C (second column), and the difference between the ORA20C and the PlaSim-LSG raw fields (third column), over a 25-year period. This is shown for the surface temperature in °C (first row), depth temperature in °C (second row), surface salinity in psu (third row), and depth salinity in psu (fourth row).

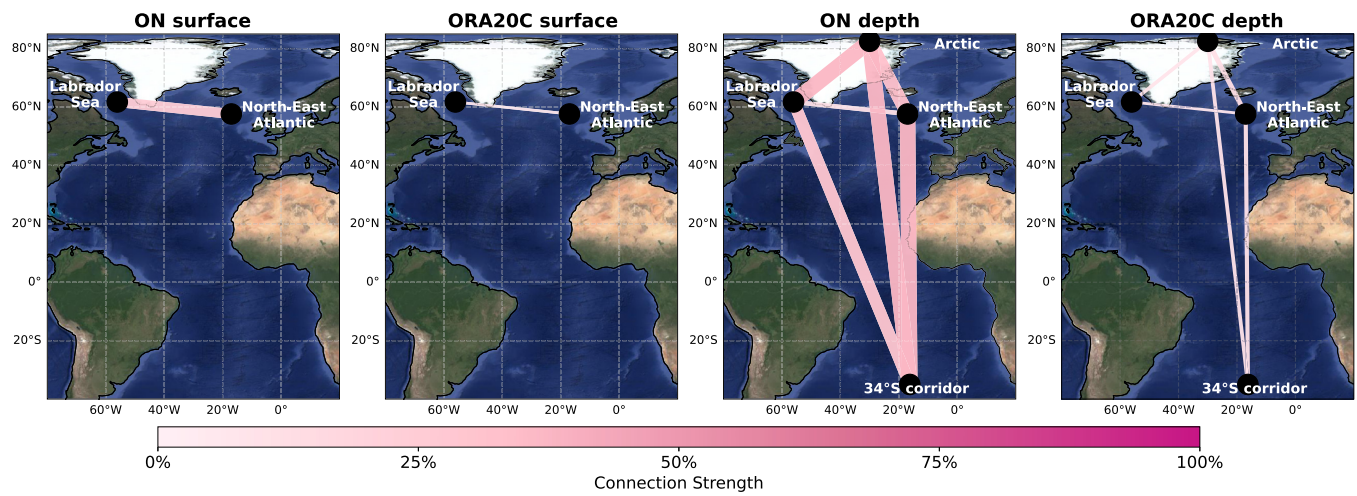


FIG. 7. Region-to-region temperature connections for the ON state at the surface, ORA20C at the surface, the ON state at depth, and the ORA20C at depth, respectively. The darkness of the pink color and the thickness of the connecting lines are proportional to the connection density. A 5% threshold has been applied to remove the noise. The region labels are the ones displaying connections with other regions.

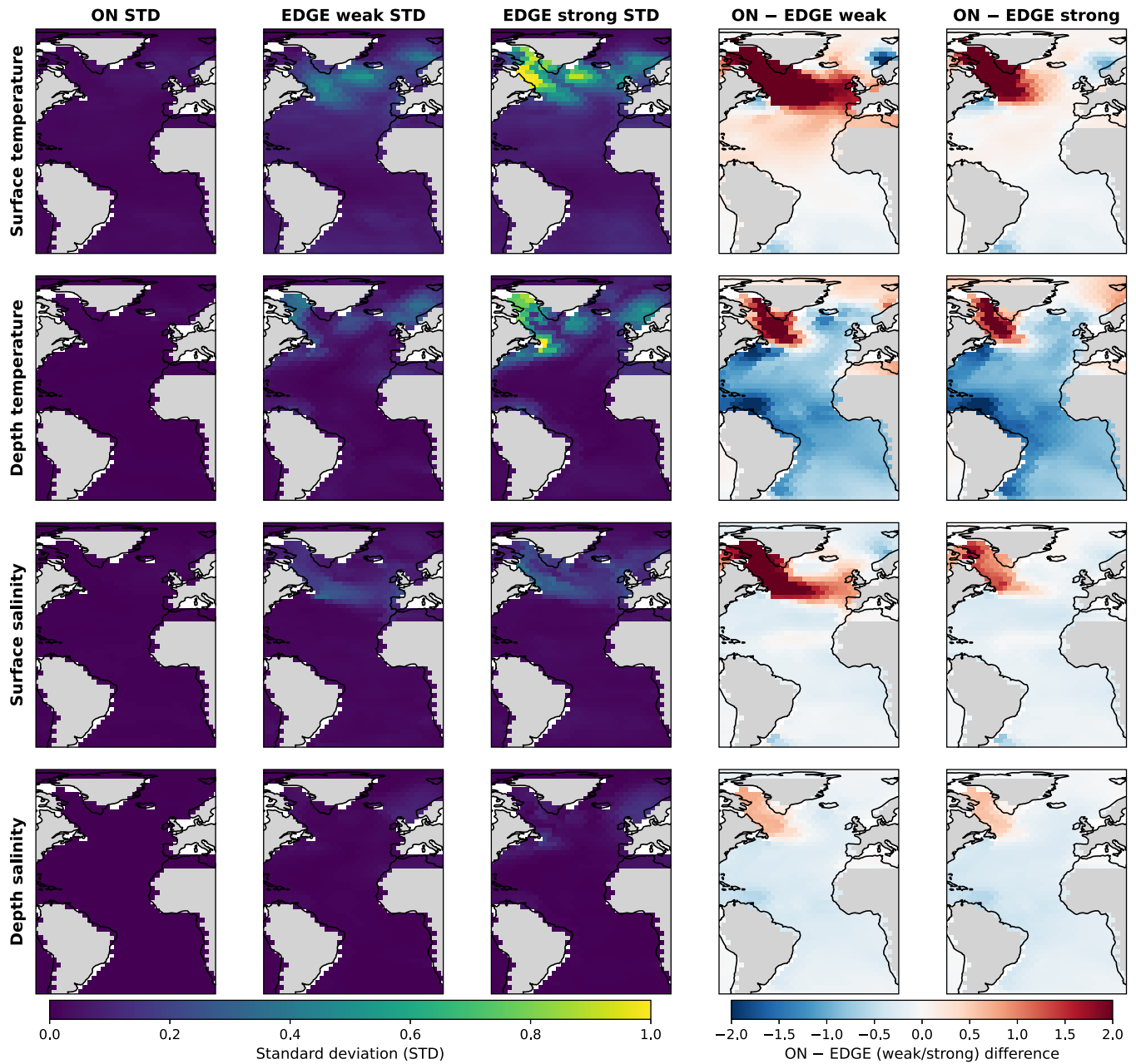


FIG. 8. Raw-field standard deviation (STD) for the ON (first column), EDGE weak (second column), and EDGE strong (third column) states obtained with PlaSim-LSG. Differences in the raw fields between the ON and EDGE weak (fourth column) and EDGE strong (fifth column), respectively. This is shown for the surface temperature in $^{\circ}\text{C}$ (first row), depth temperature in $^{\circ}\text{C}$ (second row), surface salinity in psu (third row), and depth salinity in psu (fourth row).

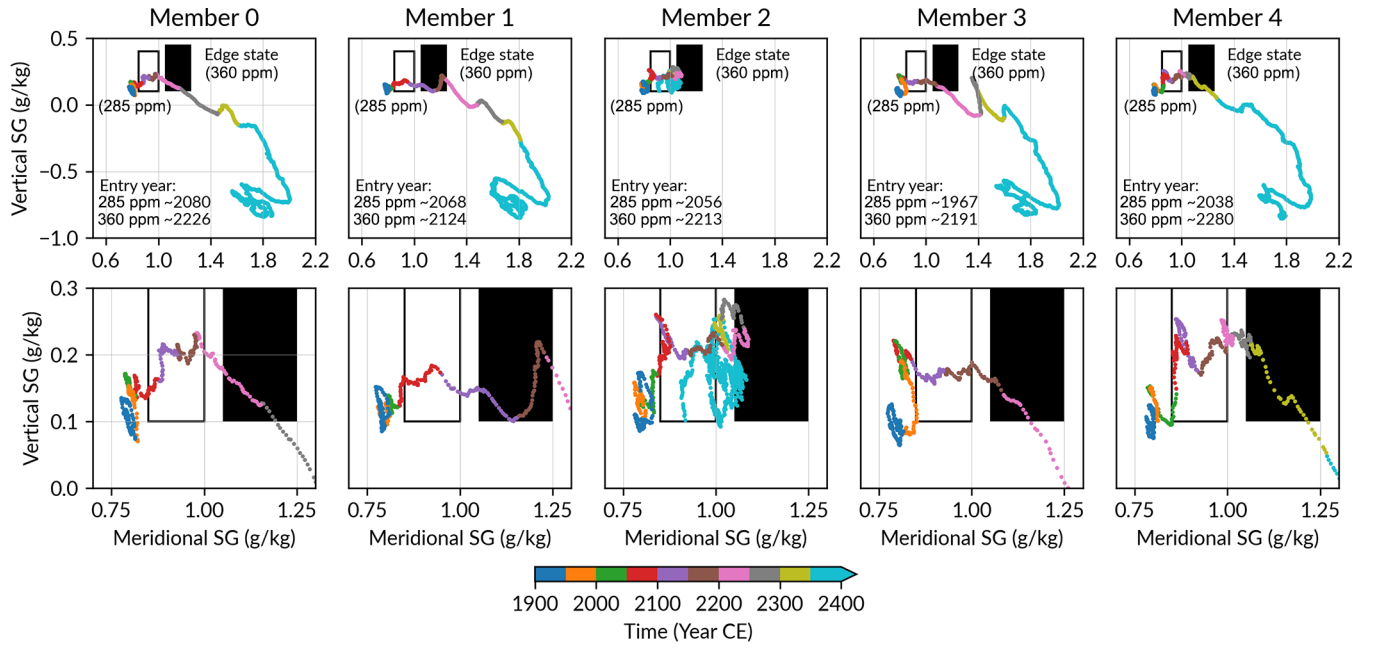


FIG. 9. Trajectories of the PlaSim-LSG ensemble (shown in Fig. 4) under SSP2-4.5 CO₂ forcing, plotted here in the reduced phase space of the meridional salinity gradient (SG) and vertical SG (see Ref. [10]) and colored by time. The black-framed (filled) rectangle indicates the EDGE-state region at 285 ppm (360 ppm). The time of first entry into these regions is listed in each top panel (in the case of member 3, the time of second entry, 2109, is indicated in Figs. 4, 10, and 11). Bottom panels display close-ups of the respective top panel.

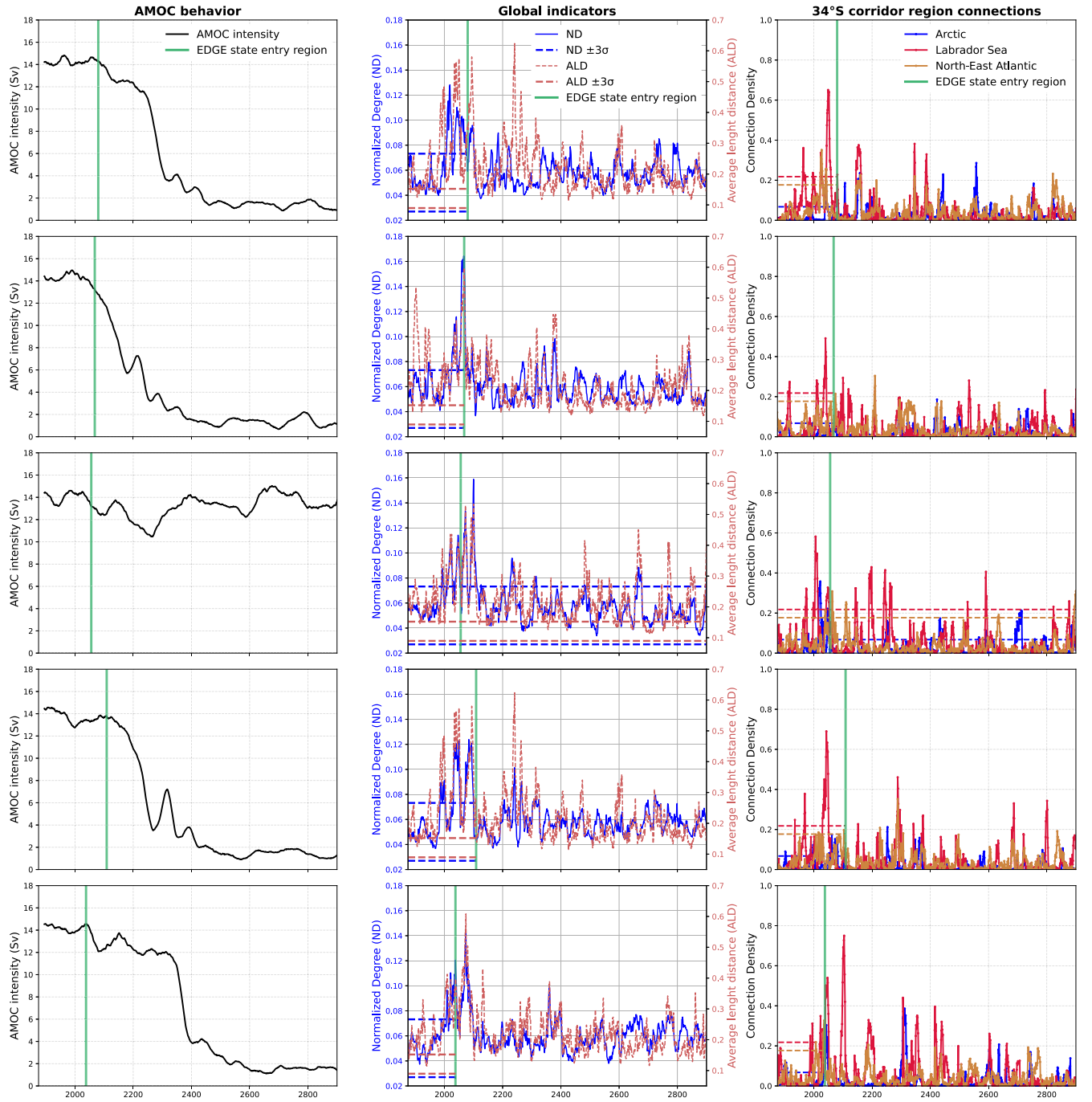


FIG. 10. Same as Fig. 4 in five PlaSim-LSG simulation ensembles with a moving time window of 25 years.

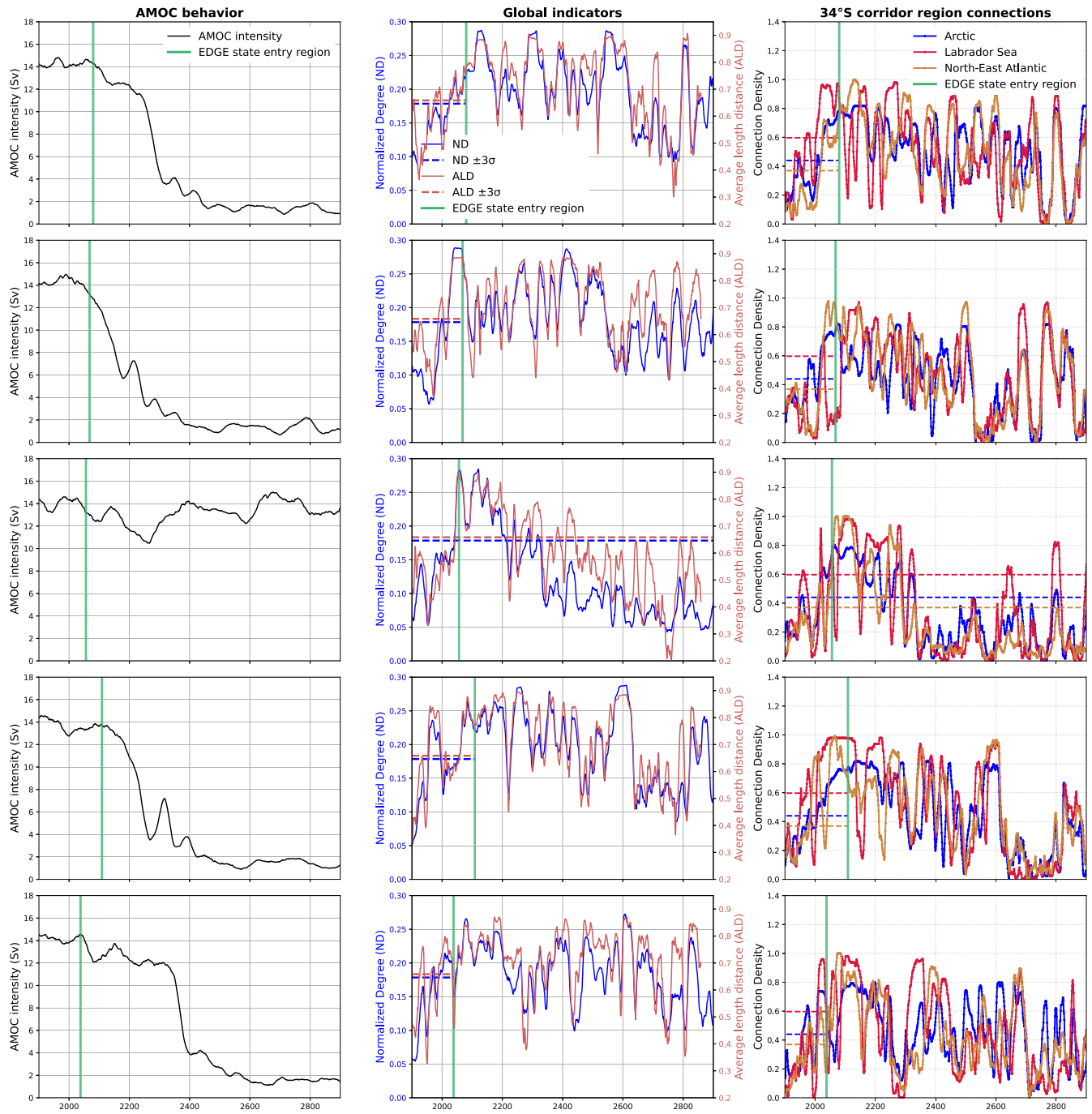


FIG. 11. Same as Fig. 4 in five PlaSim-LSG simulation ensembles with a moving time window of 50 years at depth.

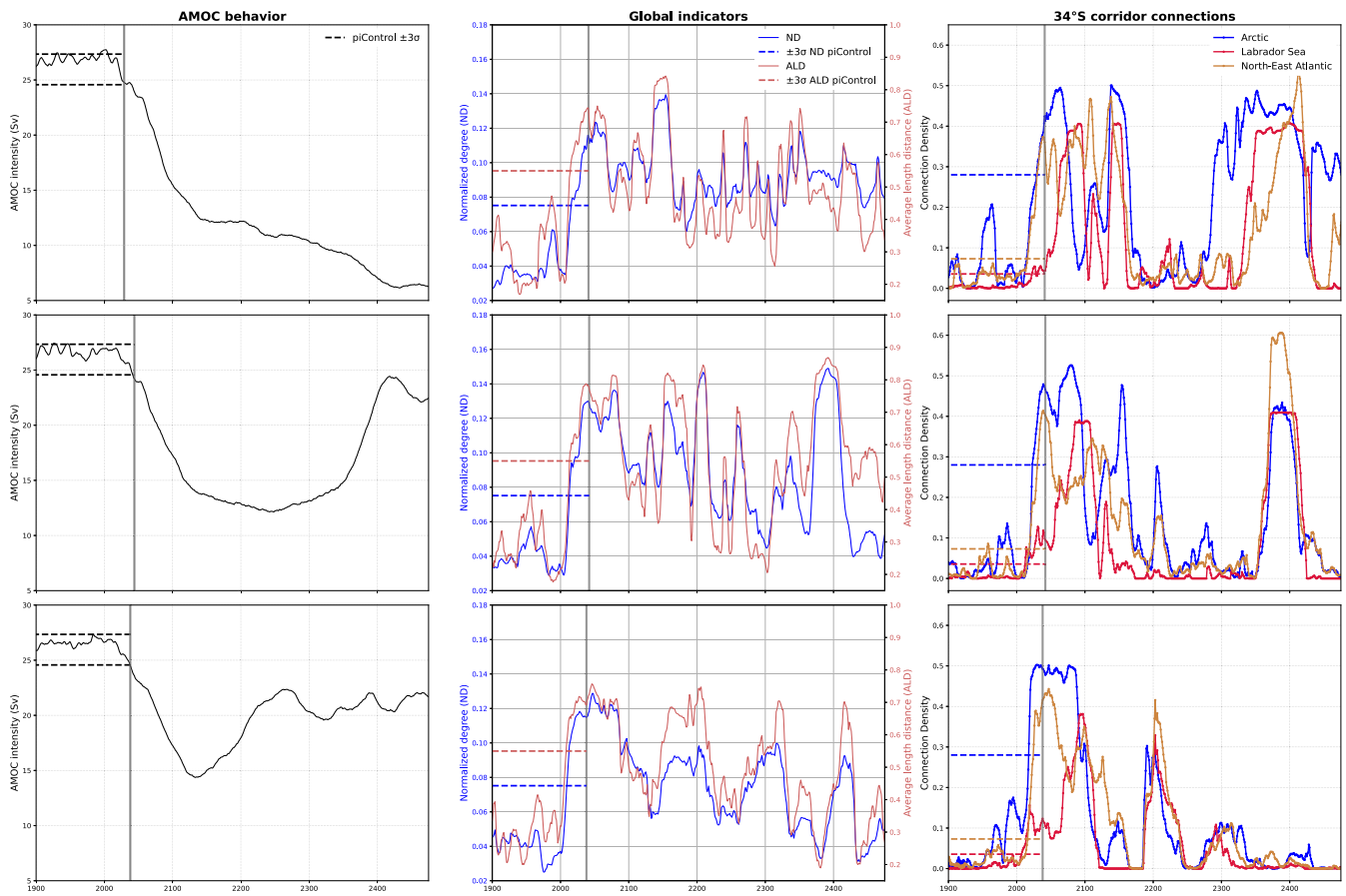


FIG. 12. Same as Fig. 5 in three NASA-GISS simulation ensembles with a moving time window of 50 years at depth.

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