

**Review of the manuscript** “Extracting coherent spatio-temporal modes of simulated multi-centennial AMOC variability under constraints that reflect sparsity of proxy data”, *by*: Toon Bense, Henk A. Dijkstra, **and Pepijn Bakker**

### **Overall assessment**

In the manuscript is investigated whether multichannel singular spectrum analysis (MSSA) can recover multi-centennial modes of simulated Atlantic Meridional Overturning Circulation variability when model output is sampled only at locations where suitable marine temperature proxy records exist. The authors first diagnose variability in a 3000-year iLOVECLIM simulation, then compare MSSA results obtained from complete spatial fields with results from a 35-cell “Proxy Grid” and from Monte Carlo subsets of that grid. Thus, it is tested how spatial sparsity affects MSSA.

The manuscript is well structured, the MSSA introduction is accessible, and the attempt to evaluate both mode detection and phase-pattern recovery is valuable. The perfect-model framework is appropriate as an initial methodological step and the conceptual explanation of SSA, PCA, and MSSA is useful for paleoclimate readers. However, as presented below, some aspects need further clarifications. Therefore, I recommend **major revision**.

### **Major comments**

1. The concept of “mode of variability” is often used. A definition for it is useful. How is defined a mode of variability?
2. Para 35: Why different frequencies identified with SSA can be considered modes? If an analyzed signal has no harmonic shape, then a spectral analyzes could provide spurious peaks which do not reflect physical modes, but only a mismatch between the non-harmonic shape of the input signal and the shapes of the functions of the basis (harmonics).
3. What are the advantages of using SSA relative to other spectral methods? What are the advantages of using PCA?
4. Yes, PCA provides a pattern associated only with a phase of a mode, whereas MSSA provides a dynamical picture of the mode’s evolution. However, one could derive such a dynamical picture, for example. by constructing lagged regression maps based on the time component of the mode. This is much simpler than MSSA. What would be the advantage of using MSSA over PCA and lagged regressions?
5. Para 345: In SSA and MSSA is common than two consecutive eigenvalues are associated with an oscillatory signal. In the manuscript on oscillatory mode was associated with eigenvalues 3 and 5. What about eigenvalue 4?
6. The manuscript identifies approximately 140-, 200-, and 280-year modes in temperature and salinity fields and calls them modes of multi-centennial AMOC variability. This is suggestive but insufficient to establish that the MSSA modes are AMOC modes rather than ocean-temperature modes that share similar periods. The authors should present more evidence that every retained MSSA mode is essentially linked with AMOC variability.

### **Minor comments**

1. Lines 27–30: The model–proxy variance discrepancy is more nuanced than an absence of internal modes. Proxy noise, temporal smoothing and spatial representativeness should also be acknowledged.
2. Lines 107–110: The omission of volcanic and solar forcing may be acceptable for a methodological test, but it makes the simulated spectral composition less representative of the real Holocene record.
3. Lines 117–121: Replace “criteria” with “criterion.” Please explain how duplicates were defined and how records were mapped onto coarse grid cells.
4. Lines 190–198: The statement that T-EOFs “capture nonlinear behaviour” could be misunderstood. MSSA is a linear decomposition that can represent non-sinusoidal temporal structures; it does not infer nonlinear dynamics.
5. Equations 2–3: Please mention if the series have already been centered and standardized.
6. Lines 326–329: Please explain the reason for defining AMOC as the maximum between 45–65°N rather than using a conventional subtropical index. This definition may emphasize deep-water-formation variability rather than basin-scale overturning.
7. Lines 493–503: Please define the sign convention for “lead” more explicitly. A lead between 0 and one period is equivalent to a negative lag over the complementary part of the cycle.
8. Lines 548–555: The failure to identify one particularly harmful grid cell does not demonstrate that the lower signal-to-noise ratio is the explanation. Interactions among locations and phase cancellation may matter.
9. The manuscript would benefit from a concise table listing each proposed mode, its period uncertainty, variance explained, detection rate, variables in which it occurs, robustness across windows, and relationship with AMOC.
10. A thorough language edit is advisable. Examples include “the more known” -> “better-known,” “has previously shown” -> “has previously been shown,” “with a measures” -> “with measures,” and several instances of singular/plural disagreement.