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Simulating spontaneous AMOC collapses with a Rare Event Algorithm

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Understanding the stability of the Atlantic Meridional Overturning Circulation (AMOC) and its future development under anthropogenic forcing is of key importance for advancing climate science. Previous studies have explored the stability of the AMOC by applying external perturbations in climate models, such as freshwater hosing to the North Atlantic Ocean. However, if the system is close to losing stability, the tipping of the AMOC may also spontaneously occur via internal coupled atmosphere-ocean variability. Here, we address this hypothesis - using an innovative approach - by studying the nature of a spontaneous collapse of the AMOC in an intermediate complexity climate model (PlaSIM coupled to the LSG ocean) featuring - under pre-industrial conditions - an apparently stable state. Excluding all possible external forcing elements (for example green-house gasses increase, water hosing, radiative forcing anomalies), significant AMOC slowdowns and collapses can be treated as extreme events solely driven by the chaotic internal atmospheric variability. Facing this problem, we look for extreme AMOC slowdowns by applying a Rare Event Algorithm (Ragone, Wouters and Bouchet, 2018), which - via a selective cloning of the most interesting model trajectories - allows a faster exploration of the model phase space in the direction of an AMOC decrease.

After exploring the parameters of the rare event algorithm, we find a regime in which PLASIM/LSG shows an abrupt AMOC slowdown over a 20-years period to a substantially weakened state, which is unprecedented in the pre-industrial run. Stability analysis reveals that part of these slowdown states are actually collapsed, i.e. states around a much lower value of the AMOC that do not recover to previous values.

This approach also enables us to isolate the atmospheric processes driving the AMOC slowdown, from the climate response to the weakened AMOC state. Interestingly, we find that the climatic response to internally-induced AMOC slowdowns shows strong similarities with the responses to externally forced AMOC slowdowns in state-of-the-art climate models for what concerns temperature, wind, and precipitation changes. Looking at the mechanisms causing the AMOC weakening, instead, we find that zonal wind stress over the North Atlantic is the main driver of the AMOC slowdown, via changes in Ekman transport that affect salinity and deep convection in the

Labrador sea. In this climate model, the repeated occurrence of this circulation anomaly for a few decades is sufficient to drive an AMOC collapse without possibility of recovery on multi-centennial time scales.

Overall, these results show that the methodology proposed here can be generally useful for other studies in Tipping Points since it introduces the possibility of collecting a large number of critical events that cannot be sampled using traditional approaches.