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SAI as a mean to avert AMOC collapse

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The Atlantic Meridional Overturning Circulation (AMOC) is a core component of the global thermohaline circulation, driving the redistribution of ocean heat and freshwater through deepwater formation in the high latitudes of the North Atlantic. Warnings persist that if greenhouse gas concentrations continue to rise, a rapid weakening or irreversible collapse of the AMOC by the end of the 21st century could trigger widespread climate instability, including abnormal cooling in the North Atlantic and a redistribution of tropical and Asian monsoon precipitation. In this context, this study quantitatively assesses whether stratospheric aerosol injection (SAI) can suppress or delay the risk of AMOC collapse.

Methodologically, four scenarios were designed using the CESM2 Earth System Model by varying injection volume, location, and timing. (1) SAI8T@NH: Injects 16 Tg/yr of SO₂ (roughly equivalent to the 1991 Pinatubo eruption) into the high-latitude Northern Hemisphere (45°N, 60°N @ 330°E) during 2080–2179, when AMOC bifurcation (critical point) is projected under the ZEC (Zero Emissions Commitment) pathway. (2) ZSAI (termination): Under identical conditions as (1), injection ceases in 2130, then AMOC evolution is tracked for the subsequent 100 years. (3) SAI4T@NH: SO₂ injection of 8 Tg/yr into the Northern Hemisphere high latitudes. (4) SAI4T@SH: SO₂ injection of 8 Tg/yr into the Southern Hemisphere high latitudes. A key point is that this was implemented as a pulse schedule, injecting only ‘once per year, on a single day during winter in each hemisphere’, not continuously throughout the year. Specifically, the Northern Hemisphere scenarios injected the total annual amount on January 1st each year, while the Southern Hemisphere scenarios injected it on July 1st each year.

The analysis focused on changes in surface density (surface cooling and increased salinity), deep convection intensity, density gradient, and freshwater transport in the North Atlantic, particularly the Subpolar North Atlantic (SPNA). Consequently, Northern Hemisphere injection significantly increased surface density in the SPNA through associated surface cooling and salinity increase, while strengthening deep-water convection. This effectively pushed back the AMOC’s approach to criticality and suppressed its collapse. Sensitivity to injection intensity was clearly SAI8T@NH > SAI4T@NH. The importance of spatial placement was confirmed by the fact that Southern Hemisphere injection (SAI4T@SH) failed to sufficiently induce SPNA surface density increase, leading to limited AMOC recovery.

Meanwhile, immediately after injection termination (2130), the AMOC weakened almost instantly, and a termination shock due to the abrupt removal of forcing was observed, suggesting nonlinear system responses and potential hysteresis risks. In terms of warming mitigation effectiveness, Southern Hemisphere injection showed relatively higher cooling efficiency for global mean surface temperature (GMST). However, Northern Hemisphere injection was found essential for the specific objective of stabilizing the AMOC.

In summary, SAI can serve as a temporary yet effective means to delay or prevent AMOC collapse, buying time for long-term carbon neutrality and removal strategies to take effect. However, hemispheric asymmetry, imbalances in regional benefits and side effects, and the potential for abrupt backlash upon cessation remain persistent concerns. Therefore, actual implementation necessitates sophisticated hemispheric injection strategies, cessation risk management, and the parallel implementation of complementary reduction and removal policies.

Keywords: Geoengineering, Stratospheric Aerosol Injection (SAI), Atlantic Meridional Overturning Circulation (AMOC)