Positive feedback of Gulf Stream latent heat flux in sustaining AMOC evolution under stratospheric aerosol injection

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Dear Editor,

The ocean stores more than 90% of the heat accumulated by Earth and AMOC accounts for approximately 70% of the poleward heat transport in North Atlantic, maintaining the temperate climate of the Northern Hemisphere while simultaneously transporting cold and dense deep waters southward. Global warming could result in a slowdown of AMOC due to changes in sea temperature and salinity density, and there is much interest in understanding whether and how the AMOC will decline over the 21st century. Observations from the Rapid Climate Change Programme (RAPID) AMOC show that the AMOC has declined about 12% during 2004-2018, followed by model projections of 45% additional weakening during 2090-2100 under the SSP5-8.5 scenario,[1] which may disrupt the global energy redistribution and result in severe consequences ranging from tropical cyclone, monsoon rainfall, to polar sea ice. As a complementary measure to reduce the risks from buying time to combat global warming, a serial of "climate engineering" themes—the large-scale climate interventions including carbon dioxide removal and solar radiation modification have been proposed.[2] Stratospheric aerosol injection (SAI), by mimicking the injection of sulfate aerosols from large volcanic eruptions to reflect solar radiation, has been evaluated as the primary climate intervention strategy to cool the Earth.[3] A consistent pattern emerges cross the growing body of SAI research, that SAI tends to mitigate though rarely restore greenhouse warming-induced AMOC weakening, through increased upward turbulent heat flux, reduced freshwater input, and increased air-sea temperature contrasts.[4]

Here we use the Stratospheric Aerosol Geoengineering Large Ensemble Simulations (GLENS),[3] a 20-member ensemble of SAI simulations with the objectives of maintaining the global-mean surface temperature, interhemispheric surface temperature gradient, and equator-to-pole surface temperature gradient at 2020 CE values under the Representative Concentration Pathway 8.5 (RCP8.5) scenario. Another SAI scenario, aiming to keep global mean surface temperatures at 1.5°C above preindustrial under the Shared Socioeconomic Pathway 2-4.5 (henceforth referred to as SAI-1.5)[5] is also included. GLENS uses the Community Earth System Model (CESM1) coupled with the Whole Atmosphere Community Climate Model (WACCM) while SAI-1.5 used CESM2 with a horizontal resolution of 0.95°×1.25°,[5] SO_2 is injected at four locations (30°N, 15°N, 15°S, and 30°S at 180°E) in both simulations, with the annual magnitudes calculated based on a feedback algorithm to comply with the temperature goals. As a result, a significantly larger amount of SO_2 is required under GLENS with most of the SO_2 end up at 30°N followed by 30°S, while under SAI-1.5 the SO_2 injections primarily occur at 15°S.[6]

To evaluate the relative contributions of driving force, we conduct the surface energy budget diagnosis and bulk decomposition analysis of ocean surface turbulent fluxes into the wind velocity and the air-sea specific humidity gradient.[7] The changes under each scenario are calculated relative to their defined baseline periods: 2050-2069 of GLENS compared to 2010-2030 under RCP8.5, and 2050-2069 of SAI-1.5 compared to 2020-2039 under SSP2-4.5.

AMOC EVOLUTION UNDER GLOBAL WARMING AND SAI INTERVENTION

The AMOC includes the formation and southward flow of North Atlantic Deep Water (NADW), wind-driven circulation in the subtropical and subpolar gyres, and northward return flow of upper waters notably in the Gulf Stream. Warming-induced AMOC slowdown is primarily attributed to freshwater flux from Greenland ice sheet melt, which reduces seawater density and suppresses deep ocean convection, weakening the southward transport of NADW and the compensating northward flow of upper waters in the Gulf Stream and the North Atlantic Current.[2]

The model results show that AMOC (defined as the maximum of the overturning stream function in the Atlantic Ocean at 26.5°N in this study) weakens under both RCP8.5 and SSP2-4.5 scenarios (Figure 1A), exhibiting similar weakening rates post- 2035 despite a higher equilibrium climate sensitivity and stronger ocean stratification over high latitude in CESM2, and different initial AMOC trends.

Under GLENS, the AMOC index continue to strengthen after 2030, in marked contrast to RCP8.5, reaching around 28 Sv by the third quarter of the 21th century, and remaining strengthening albeit with a slowing down rate (Figure 1A). The sustained AMOC enhancement is attributed to the significant deficient in surface water balance (i.e., precipitation minus evaporation, Figure 1B) in Northern North Atlantic including the deep-water formation zone of Labrador Sea, consistent with previous studies.[8,9] The AMOC under SAI-1.5, nevertheless, show continued decline despite a mild strengthening compared with SSP2-4.5 (Figure 1A) and a freshwater surplus across the Northern North Atlantic, compared to the baseline period (Figure 1C). This raises the question of whether the different AMOC responses primarily reflect differences in the design of the intervention, such as the total sulfate burden or the latitude of injection, or whether additional processes also contribute to this divergence.

LINKAGES BETWEEN FRESHWATER FLUX AND LATENT HEAT RESPONSES

The LH transfers approximately 23% of the incoming solar radiation from the ocean to the atmosphere through evaporation, and serves a primary role in balancing the ocean's net heat. Gao & Gao demonstrated that while ocean LH response generally compensates for volcanic-induced radiative cooling,[7] LH release is intensified over GSE (the region between 40ºN~60ºN and 20ºW~60ºW), where SST is controlled mainly by advection rather than surface heat flux, meaning that LH responds to, rather than drives, SST change. Here we show that the LH responses over GSE exhibit similar trends as the AMOC strengths (Figure 1D)—LH loss increases and remains elevated under GLENS. Spatially, regions of freshwater deficit coincide with increasing LH release (Figure 1E) due to enhanced evaporation.

Model results reveal an anomalous surface water convergence and positive potential density anomalies in the ocean's upper 1,000 m under GLENS, particularly near southern Greenland, which suggests a direct role for salinity in driving the enhanced circulation.[7] As the main engine of poleward heat transport, a stronger AMOC increases the northward advection of warm surface waters, which sustain relatively high SSTs over GSE despite the overall radiative cooling (Figure 1E). The warm SSTs maintain a large air-sea

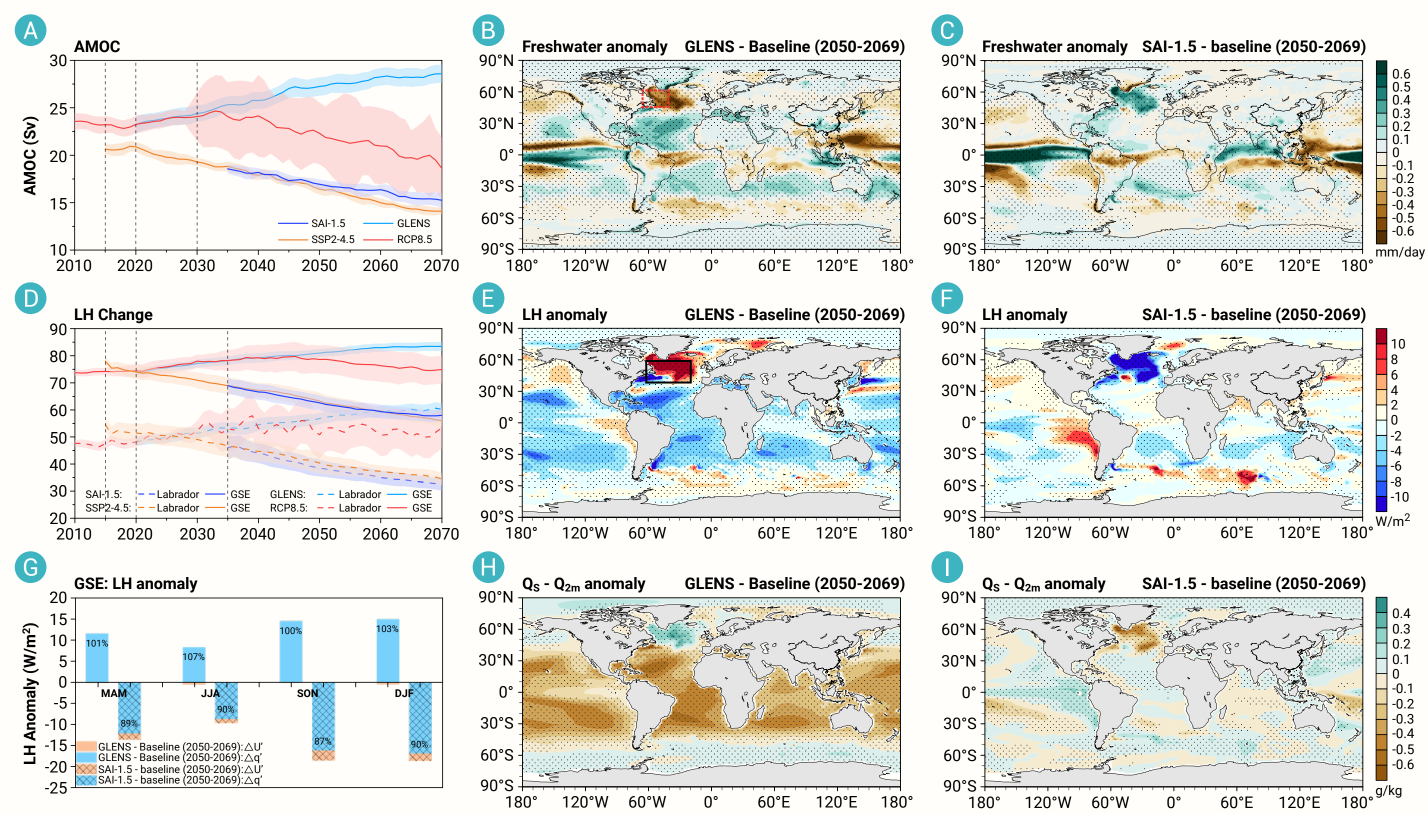

Figure 1. Evolution of AMOC under global warming and SAI climate intervention, and the role of latent heat flux (LH) in Labrador Sea (47ºN~60ºN, 45ºW~67ºW, marked by the red rectangle in panel B) and Gulf Stream Extension (GSE between 40ºN~60ºN and 20ºW~60ºW, marked by the black rectangle in panel D) Simulated changes in AMOC strength (A), the 9-yr running mean LH responses in GSE and Labrador Sea regions (solid and dashed lines in D, respectively) under RCP8.5, SSP2-4.5 and two SAI scenarios. Spatial patterns of freshwater flux (B & C) and LH anomalies (E & F) under GLENS and SAI-1.5 scenarios, respectively. Relative contribution of the surface wind (orange bar) and air-sea relative humidity gradient (blue bar) to the GSE-LH anomalies (G), and the spatial pattern of air-sea relative humidity gradient (H & I) under GLENS and SAI-1.5 scenarios. Ocean release of heat flux to the atmosphere is defined as positive for LH flux.

temperature and humidity gradient, reinforcing evaporation and latent heat release. Together, these processes establish a positive feedback loop that sustains enhanced AMOC under GLENS.

DIFFERENCE IN THE LATENT HEAT RESPONESES AMONG VARIOUS CLIMATE SCENARIOS

Changes in LH flux can be decomposed into contributions from oceanic responses and atmospheric forcings.[7] In a warming climate, near-surface humidity (Q_{2m}) plays a significant role in modulating the rate of LH exchange. Evaporation occurs only when Q_{2m} is lower than surface saturation humidity (Q_s), while surface winds help maintain the air-sea humidity gradient by carrying the water vapor away from the sea surface. Our bulk decomposition analysis shows that the air-sea humidity gradient dominates both the LH anomalies and the intra-scenario differences (Figure 1G). Spatially, the LH response pattern over the northern Atlantic echoes the anomalies in air-sea specific humidity gradient (Figure 1H). A similar positive feedback applies under SAI-1.5, but in the opposite way (Figures 1A, C-D, & F): the initial weakening of AMOC cools the SST in northern Atlantic, reduces Q_s more effectively than Q_{2m}, and suppresses evaporation (Figure 1I). The initial difference in AMOC between GLENS and SAI-1.5 could be due to the different intervention starting year and model versions, and the long-term evolution is likely related to the latitudinal location of most injections (30°N under GLENS vs. 15°S under SAI-1.5), which has been shown to strongly influence AMOC strength.[9]

Latent heat flux links air-sea heat exchange with the hydrological cycle, and understanding the distinct signatures of LH associated with AMOC under various climate scenarios is crucial given its broad implications for global heat and moisture budgets. Here we demonstrate LH response in GSE as a self-reinforcing loop which sustains AMOC evolution under different SAI scenarios. Our results show the high sensitivity of surface saturation specific humidity to SST variations in this upper-layer portion of AMOC, and offer a new perspective for evaluating AMOC evolution under anthropogenic warming or climate intervention scenarios.

The relationship between the AMOC and global heat distribution remains a critical and active area of climate research. Ref.[10] suggests that radiative cooling from increased Asian anthropogenic aerosols drives an AMOC reduction, via generating circumglobal stationary Rossby waves which shift the midlatitudes westerly jet stream southward and weaken the subpolar North Atlantic westerlies. The forced responses in CESM1-WACCM depend strongly on regional projections of the water cycle and surface winds,[8] thus its estimations of AMOC variability and trends may have inherited uncertainties, with potentially important model dependencies. Future study with high-resolution or eddy-scale model, under targeted injection scenarios, is needed to further verify the proposed feedback mechanism and reconcile the stratospheric vs. tropospheric aerosol effects. In addition, this study focuses only on the vertical freshwater budget (i.e., precipitation minus evaporation). Although GLENS largely maintains the high - latitude sea ice and glaciers of both hemispheres, potential residual influence on surface water salinity merit further investigation.

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AUTHOR CONTRIBUTIONS

C.G. conceived of the study and wrote the manuscript with input from other co-authors. Y.G. processed and analyzed the data. L.X. provided interpretative guidance. All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.