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LETTER

Linking Antarctic sea ice expansion to high-latitude Southern Ocean surface cooling and salinification

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Dear Editors,

Antarctic sea ice remains an indispensable puzzle piece in understanding regional and global climate. It experienced a slight but statistically significant increase since the satellite era,[1] then dwindled precipitously in 2016, and appears to be entering a new decline stage.[2] In 2023, the Antarctic sea ice winter maximum hit a record low. Such dramatic sea ice changes have far-reaching consequences for Antarctica and the rest of the world, profoundly influencing climate, ecology, and society.

The recent decline of Antarctic sea ice, which mirrors the decline of its counterpart in the Arctic, may make sense in light of global warming. What remains mysterious, however, is the expansion preceding the decline. Antarctic sea ice expansion has been linked to both external climate forcing and internal climate variability. The former encompasses Antarctic glacial melt[3] and changes in the Southern Annular Mode (SAM) engendered by anthropogenic greenhouse gas emissions and stratospheric ozone depletion, whilst the latter is tied mainly to deep convection variability in the Southern Ocean and climate variability in the Pacific and Atlantic Oceans.[4]

During the same period when Antarctic sea ice expanded (Figures 1A-B), sea surface temperatures (SSTs) in the Southern Ocean displayed a slight but significant cooling trend (Figure 1E). This surface cooling has been attributed primarily to similar drivers of Antarctic sea ice expansion,[5] such as freshwater discharge from the Antarctic ice sheet, SAM-induced surface westerly wind changes, and Southern Ocean convection variability. It is also connected, via atmospheric teleconnection processes, to the surface cooling in the tropical southeast Pacific.

Albeit aforementioned mechanisms, current climate models collectively struggle to reproduce the observed Antarctic sea ice expansion and Southern Ocean surface cooling. Most models under historical climate forcings simulate a diminished Antarctic sea ice cover[6] and a warming SST trend across the Southern Ocean.[5] Such model-observation discrepancies hamper model's fidelity in assessing and projecting the on-going and future climate changes, and meanwhile, raise critical scientific questions: Will a simulated Antarctic sea ice expansion render a concomitant Southern Ocean surface cooling? Or more specifically, to what extent can the model bias of Antarctic sea ice trend explain its bias of Southern Ocean SST trend? In addition to SST, how will Antarctic sea ice expansion affect the sea surface salinity (SSS) trend in the Southern Ocean?

To address these scientific questions, I first look at and into the passive microwave monthly Southern Hemisphere sea ice concentration by NASA Team algorithm processed by the National Snow and Ice Data Center (NSIDC), which is gridded on the NSIDC polar stereographic grid with 25 km × 25 km grid cells. I examine annual mean values of sea ice concentration from 1979 to 2013 and the total Antarctic sea ice area—a metric independent of model grid and resolution—during this span. I also adopt the EN4 (version 4.2.2) ocean temperature and salinity analysis from 1979 to 2013, which has a horizontal resolution of 1 degree with 42 vertical levels on a full-depth ocean. I choose this dataset seeing that it provides consistent analyses of ocean temperature and salinity. As the EN4 dataset is available in four versions, I depict it by taking the average of the four versions. I use 5-m ocean temperature and salinity to represent sea surface temperature and salinity.

I leverage a broadly used climate model, CESM1-CAM4 (CESM1 for simplicity), with a ~1-degree atmosphere and a nominally 1-degree ocean/sea ice. I perform CESM1 historical and Representative Concentration Pathway 4.5 (RCP45) simulations over 1950-2013 in which the model is driven by historical climate forcings during 1950-2005 but RCP45 climate forcings afterwards. I generate 10 ensemble members for these simulations combining macro and micro initialization methods: simulations start from 4 different model states in 1950, and for each state, slight perturbations are introduced only to the atmosphere component. The CESM1 ensemble mean delineates a decrease in the Antarctic sea ice area at a rate of -0.34 ± 0.12 million km^2/decade (ensemble mean ± one standard derivation among ensembles, Figure 1A) between 1979 and 2013, in line with the sea ice decline trend evinced by most climate models[6] but at odds with the observed sea ice increase trend (0.17 million km^2/decade, Figure 1A). For a practice that has come to epitomize the aforementioned climate model bias, CESM1 simulates a pervasive sea ice loss around Antarctic (Figure 1D), whereas observations reveal robust sea ice increases in the Weddle, Lazarev, Rillser-Larsen, Cosmonauts, Cooperation, D'Irville, Somov and Ross Seas (Figure 1B).

Based on CESM1 historical and RCP45 simulations, I modify the model by enlarging the emissivity of sea ice and overlying snow only over the Antarctic sea ice area to augment the outgoing longwave radiation since 1979 (referred to as "CESM1-ASI", with 10 ensembles over 1979-2013). Particularly, I increase the emissivity of snow and ice by a time-evolving factor of [1.2 + (year − 1979) × 0.05] over the Antarctic sea ice area under the historical and RCP45 scenarios where year denotes the year index within the period of 1979-2013. This modification's concept was inspired by an earlier ensemble pacemaker experiment,[7] which took tropical variability into account, elucidated how the forced response of Antarctic sea ice dominates its trend in each ensemble member, making none of the ensemble members resemble the real world, and indicated that the Antarctic sea ice in their model overly sensitive to external forcing. My modification of sea-ice/snow radiative properties can be viewed as ice forcing, adjusting the model to reflect the correct response of Antarctic sea ice to external forcing. Importantly, this method allows for natural atmosphere-ice-ocean coupling as well as investigation of the effect of Antarctic sea ice on Southern Ocean SST and SSS.

Between 1979 and 2013, CESM1-ASI presents an increasing trend in Antarctic sea ice area of 0.14 ± 0.09 million km^2/decade (ensemble mean ± one standard derivation among ensembles), which well aligns with observations, even though the simulated sea ice area may differ slightly from observations on shorter decadal timescales (Figure 1A). Except for the Weddle Sea and a portion of the Ross Sea, the simulated sea ice expands in the observed areas (Figure 1C). One notation occurs over the Amundsen and Bellingshausen Seas, where sea ice exhibits strong decadal oscillations,[8] with CESM1-ASI and observation depicting sea ice expansion and decline, respectively. The discrepancy between CESM1-ASI and observation potentially reflects their difference in tropical Pacific teleconnection as well as local wind pattern.[8]

The expansion of Antarctic sea ice in CESM1-ASI causes a notable SST cooling primarily south of 60ºS in the Southern Ocean (Figure 1F), which is distinct from the general Southern Ocean SST warming in CESM1 (Figure 1G) and many other climate models.[5] This finding suggests that Antarctic sea ice expansion between 1979 and 2013 is only related to Southern Ocean surface cooling up to around 60ºS, but not further north. Surface cooling north of 60ºS, on the other hand, might be attributed to other factors such as tropical variability.[4]

The simulated Antarctic sea ice expansion in CESM1-ASI also brings on a conspicuous increasing trend of surface salinity from the Antarctic coast to 60ºS and a surface freshening trend north of 60ºS in the Southern Ocean (Figure 1I), as consistent with the pattern of observed SSS change[3] (Figure 1H). The underlying rationale is that sea ice forms around the Antarctic coast,

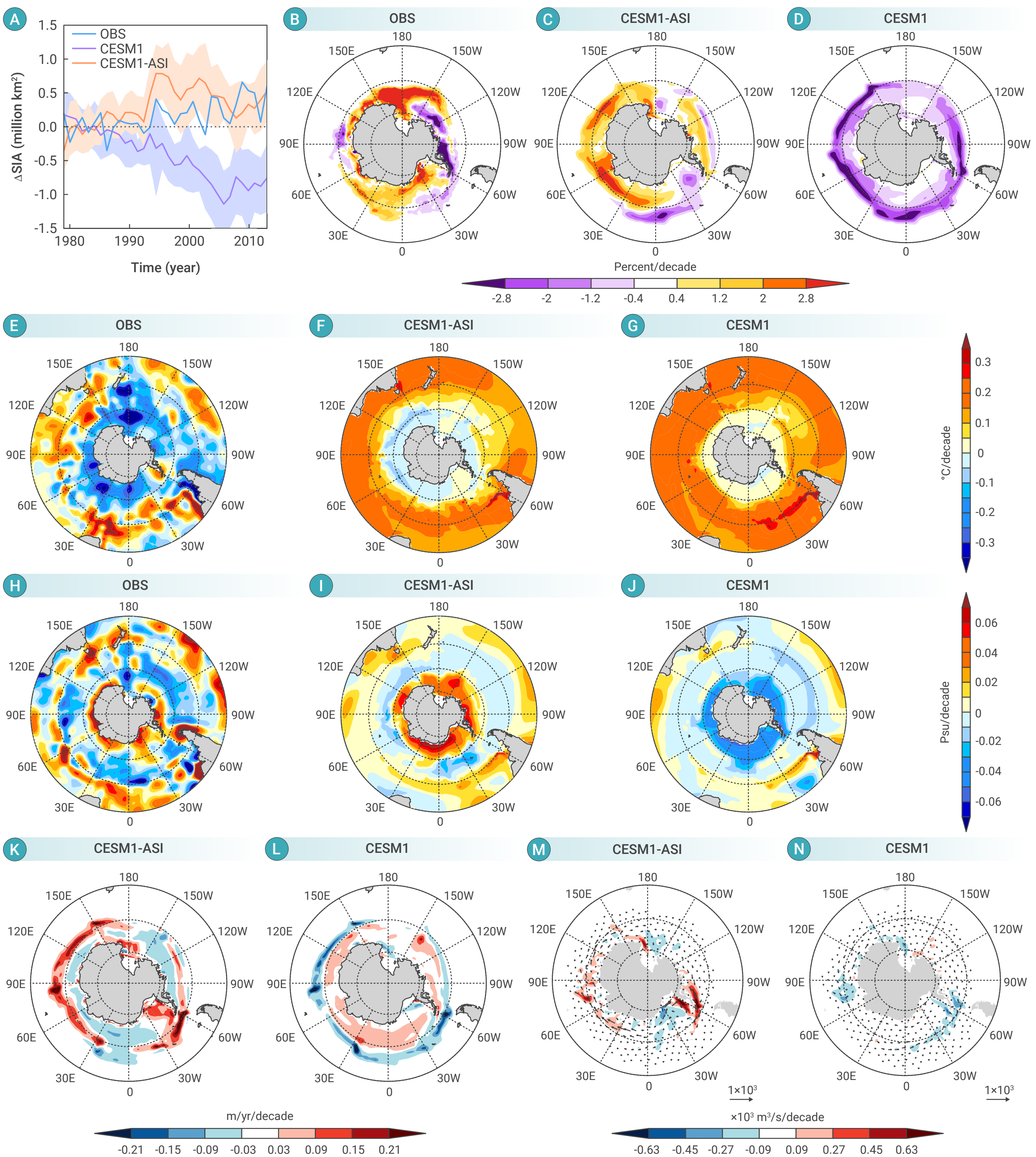

Figure 1. Observed and simulated Antarctic sea ice and Southern Ocean SST and SSS changes (A) Anomalies (relative to the 1979-1988 average) in annul mean Antarctic sea ice areas from NSIDC observations (blue), CESM1 (ensemble mean, purple; ensemble spread, light purple), and CESM1-ASI (ensemble mean, orange; ensemble spread, light orange). The ensemble spread is calculated as one standard deviation among ensembles. (B-D) Annual mean sea ice concentration trends over 1979-2013 for (B) NSIDC observations, (C) CESM1-ASI and (D) CESM1 ensemble means. (E-G) Linear trends of annual mean SST over 1979-2013 (contour shading in °C/decade) from (E) EN4 observations, (F) CESM1-ASI and (G) CESM1 ensemble means. (H-J) Same as (E-G) but for SSS trends (contour shading in psu/decade). (K,L) Trends of the net annual sea-ice–ocean freshwater flux from freezing and melting over 1979-2013 (contour shading in m/yr/decade) for (K) CESM1-ASI and (L) CESM1 ensemble means. (M,N) Same as (K,L) but for trends of annual sea-ice freshwater transport. The arrows show the trends of the annual transport vectors (reference vector: 1×10^3 $m^3/s/decade$), and the contour shadings (in $\times10^3$ $m^3/s/decade$) show the trends of the annual meridional transport.

moves northward due to meridional wind drift, and melts in the open ocean in lower latitudes. Between 1979 and 2013, CESM1-ASI witnesses a large trend of equatorward sea-ice freshwater transport in the Southern Ocean (Figure 1M), leading to a decreasing trend of sea-ice–ocean freshwater fluxes around the Antarctic coast but an increasing trend of freshwater fluxes to the north in the open ocean (Figure 1K), a pattern akin observational estimates.[9] In contrast to CESM1-ASI and observations, CESM1 exhibits a strong surface freshening trend to the south of 60°S (Figure 1J), little trend in meridional sea-ice freshwater transport (Figure 1N), and opposite changes in sea-ice–ocean freshwater fluxes (Figure 1L) to CESM1-ASI and observations.

To summarize, I demonstrate an intricate link between biases in trends in Antarctic sea ice, high-latitude SST and SSS over the Southern Ocean from 1979 to 2013. A reproduced Antarctic sea ice expansion is accompanied by surface cooling and salinification up to around 60 degrees south. The sea ice expansion, however, cannot account for the Southern Ocean surface cooling further north, which supports the result from a recent study.[10] Although these findings are based on a single climate model experiment, they highlight the complexities of reconciling climate models with observations and thus call for similar experiments with a broad suite of climate models to better understand the interplay between externally forced climate change and the influence of tropical climate variability.

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DECLARATION OF INTERESTS

The author declares no competing interests.

DATA AND CODE AVAILABILITY

The NSIDC sea ice data are available at https://nsidc.org/data. The EN4 (version 4.2.2) data are available at http://www.metoffice.gov.uk/hadobs/en4/index.html. The source code of CESM1-CAM4 is available at https://www.cesm.ucar.edu/. Figures are generated via the NCAR Command Language (NCL, Version 6.5.0) [Software]. (2018). Boulder, Colorado: UCAR/NCAR/CISL/TDD (https://doi.org/10.5065/D6WD3XH5).