Simulated Antarctic sea ice expansion reconciles climate model with observation

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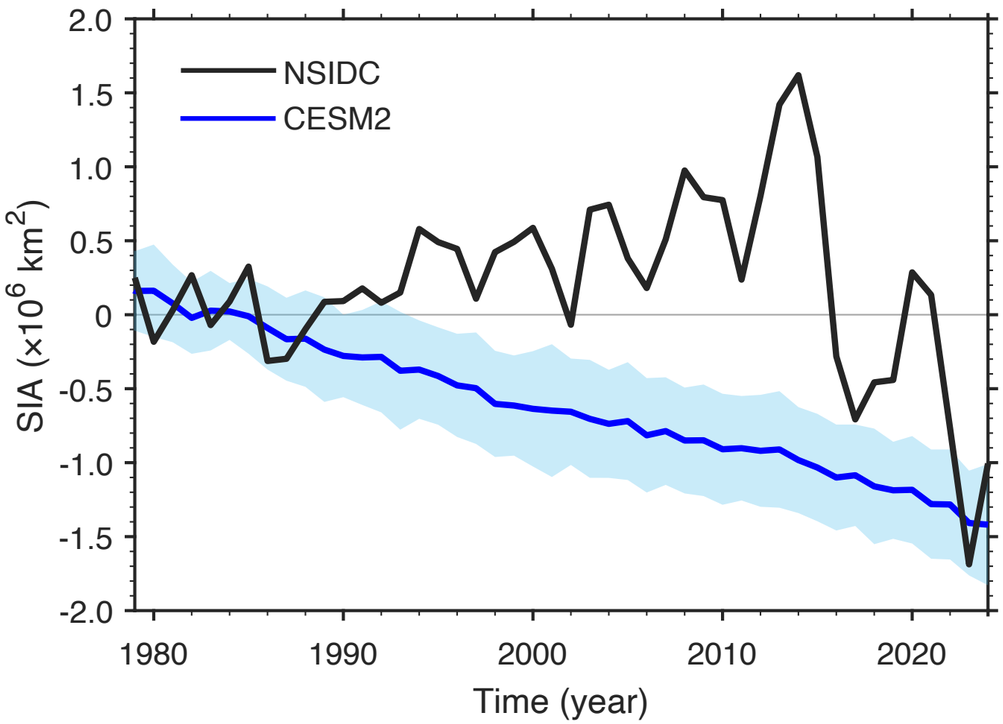
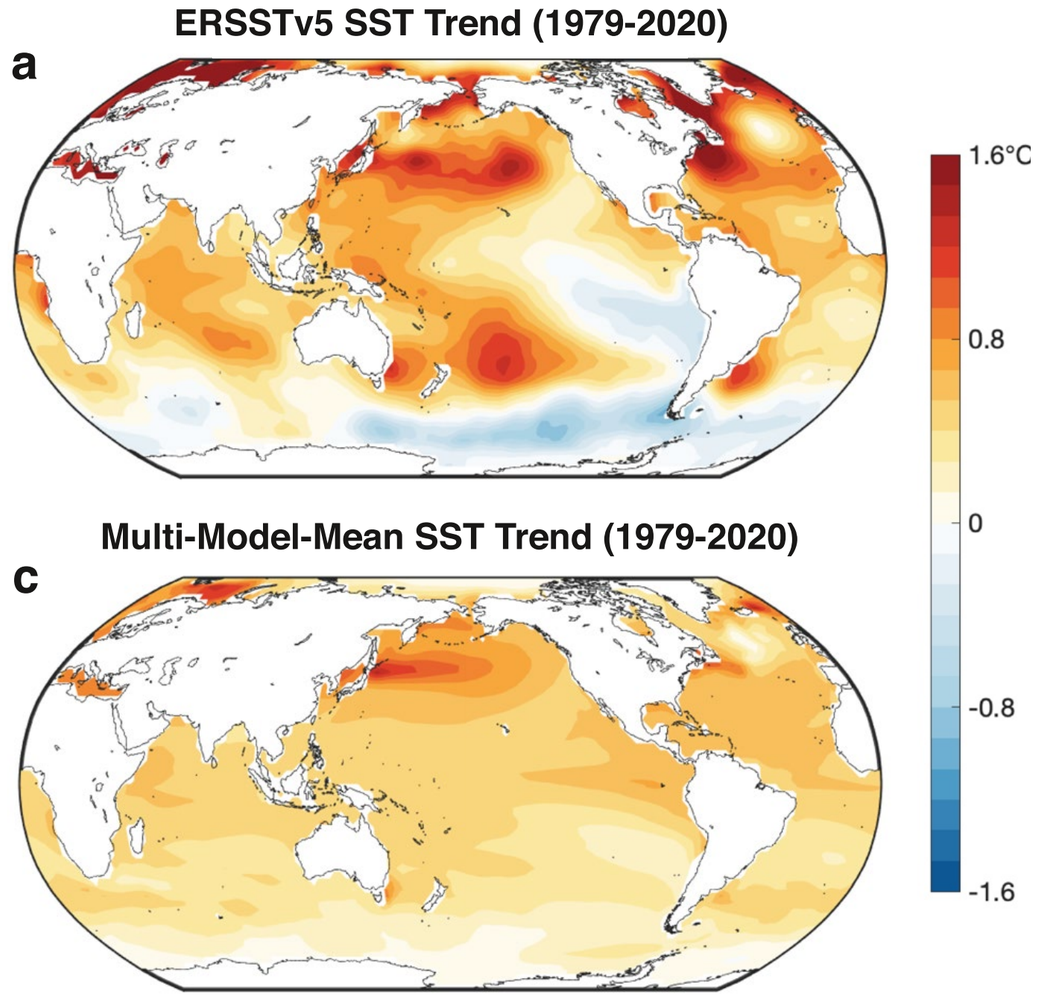
Motivation



Sea ice area anomalies (relative to the 1979-1988 average) from NSIDC observations (black), and CESM2 historical+SSP370 simulation (blue). Also, see most CMIP5 (Turner et al 2013) and CMIP6 (Roach et al. 2020) models



Wills et al. (2022)

Scientific Questions

Will a simulated Antarctic sea ice expansion render the Southern Ocean surface cool, or the other way around, given ice-ocean coupling?

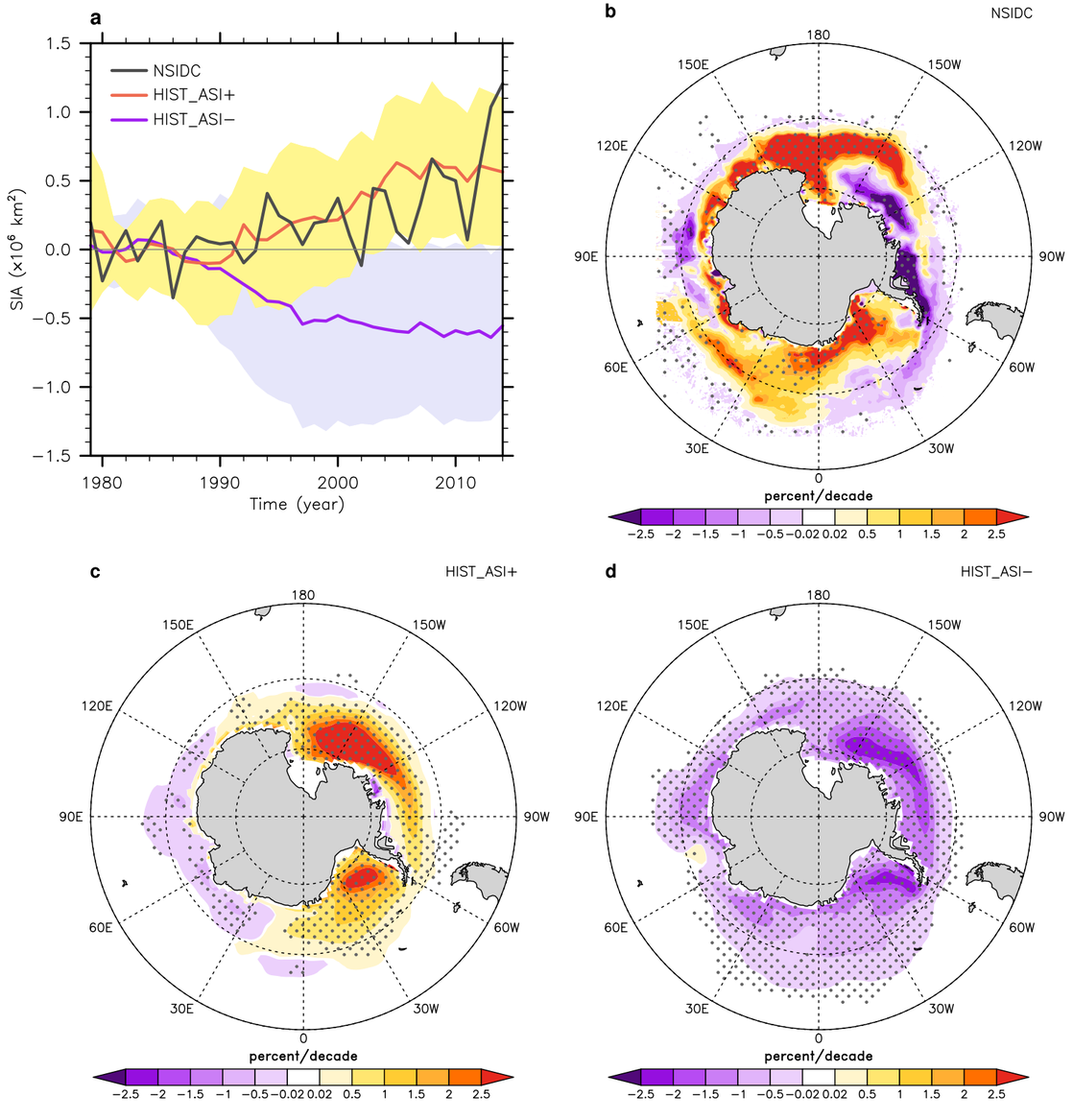
Or more specifically, to what extent can the bias of Antarctic sea ice trend account for the bias of Southern Ocean SST trend during the three to four decades since the satellite era?

How will the Antarctic sea ice expansion associate with other components of Earth's climate system?

Liu, W. (2025a) Simulated Antarctic sea ice expansion reconciles climate model with observation. npj Climate and Atmospheric Science, 8, 4.

Liu, W. (2025b) Linking Antarctic sea ice expansion to high-latitude Southern Ocean surface cooling and salinification. The Innovation Geoscience, 3, 100128-1.

Antarctic sea ice expansion due to natural sea-ice variability

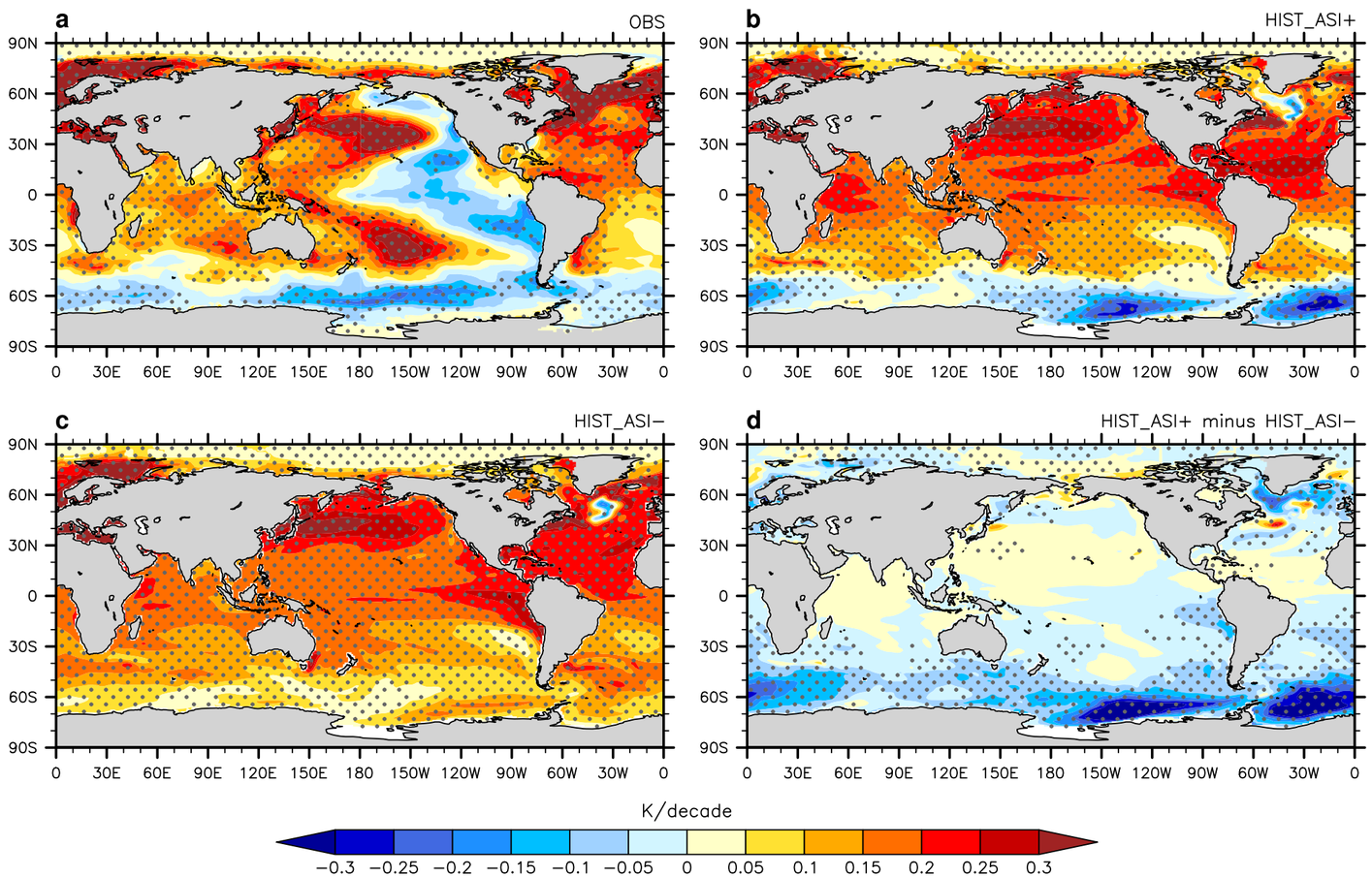


Liu (2025a)

Model	CMIP5/6	HIST_ASI+	HIST_ASI-
ACCESS-ESM1-5	CMIP6	r19i1p1f1	r(1,3,4,6,12-14,17, 21,23, 26,27,30,32,36-40)i1p1f1
CAMS-CSM1-0	CMIP6	r1i1p1f1	r2i1p1f1, r1i1p1f2
GFDL-CM3	CMIP5	r(1-4,9,11)i1p1	r(5,7,10,12-14,16,18,19)i1p1
GFDL-ESM2M	CMIP5	r(1,6,11,13,15,17,18,24-26)i1p1	r(2,4,8,16,19,20,22,27,29)i1p1
MIROC6	CMIP6	r(5,25,28)i1p1f1	r(2,29,37,40,43)i1p1f1
MIROC-ES2L	CMIP6	r(10,12,22)i1p1f1	r(4-6,8,9,17,21,25,27)i1p1f1

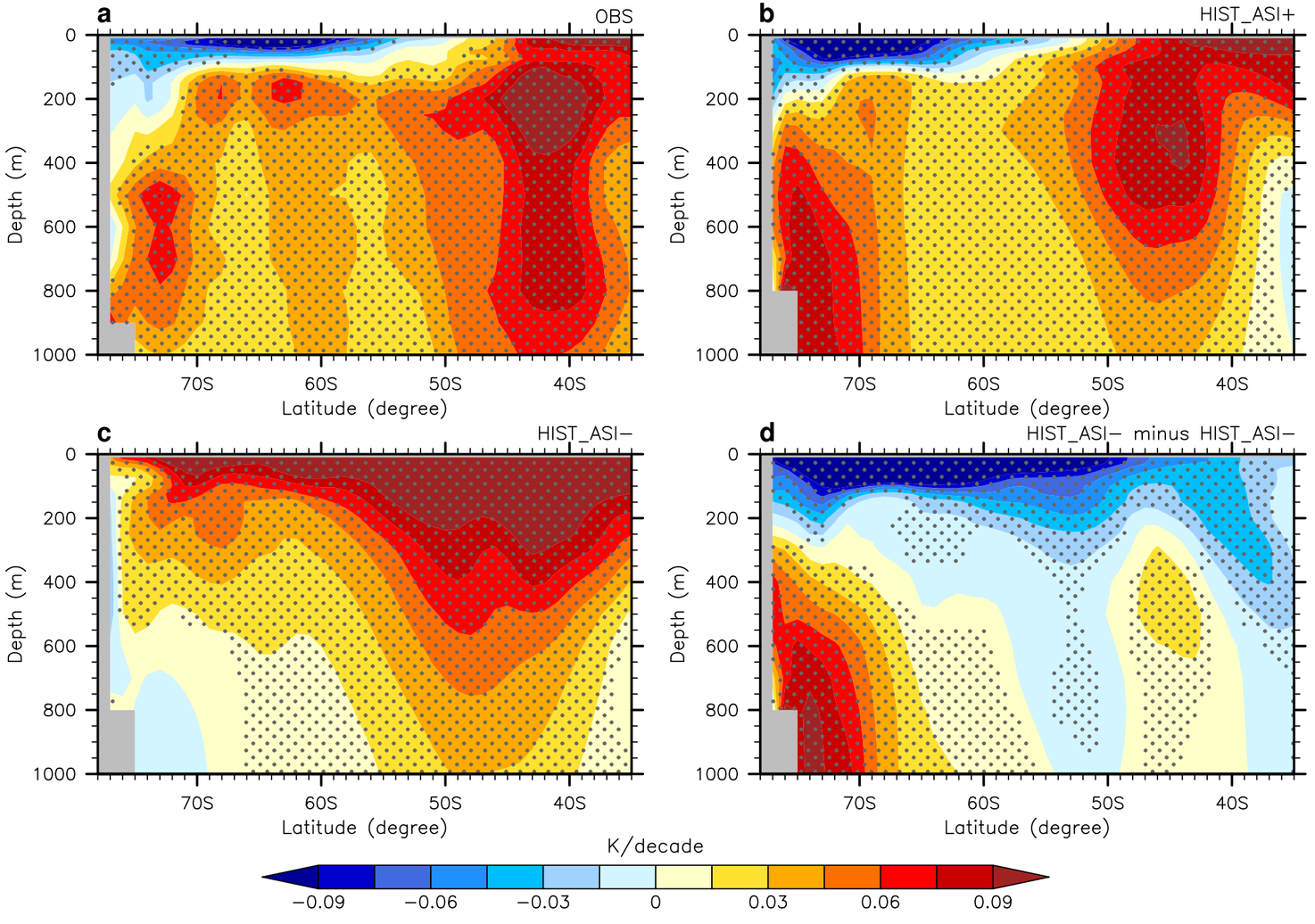
- Historical ensemble simulations with multiple climate models show that sea-ice natural variability enables the models to simulate an Antarctic sea ice expansion during 1979-2014 under anthropogenic forcings
- This highlights the variability mechanism in an approach without interfering the natural atmosphere-ice-ocean coupling, thus different from many previous studies

Linked to high-latitude Southern Ocean SST cooling



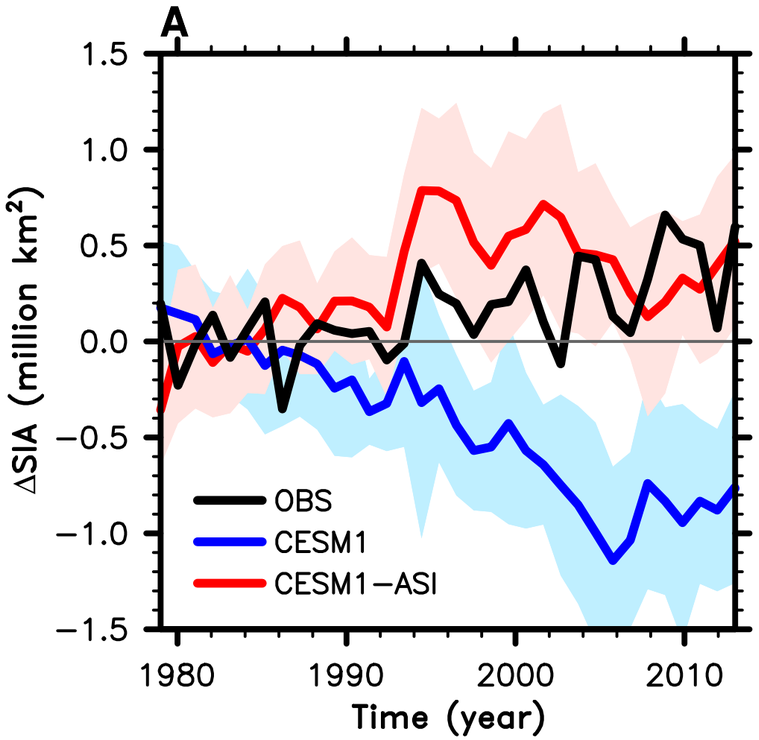
- Antarctic sea ice expansion is linked to a Southern Ocean SST cooling primarily to the south of around 50°S
- SST cooling north of 50°S could be associated with factors such as tropical Pacific variability
- The difference reveals negative SST trends not only across the Southern Ocean but also in the tropical south Pacific and south Atlantic, implying teleconnections between the Southern and tropical oceans. Compared to retreating ice, Antarctic sea ice expansion has a cooling effect on tropical Pacific and Atlantic SST, but it is insufficient to offset the background anthropogenic warming or modelled tropical climate variability

Improved simulation of subsurface temperature change



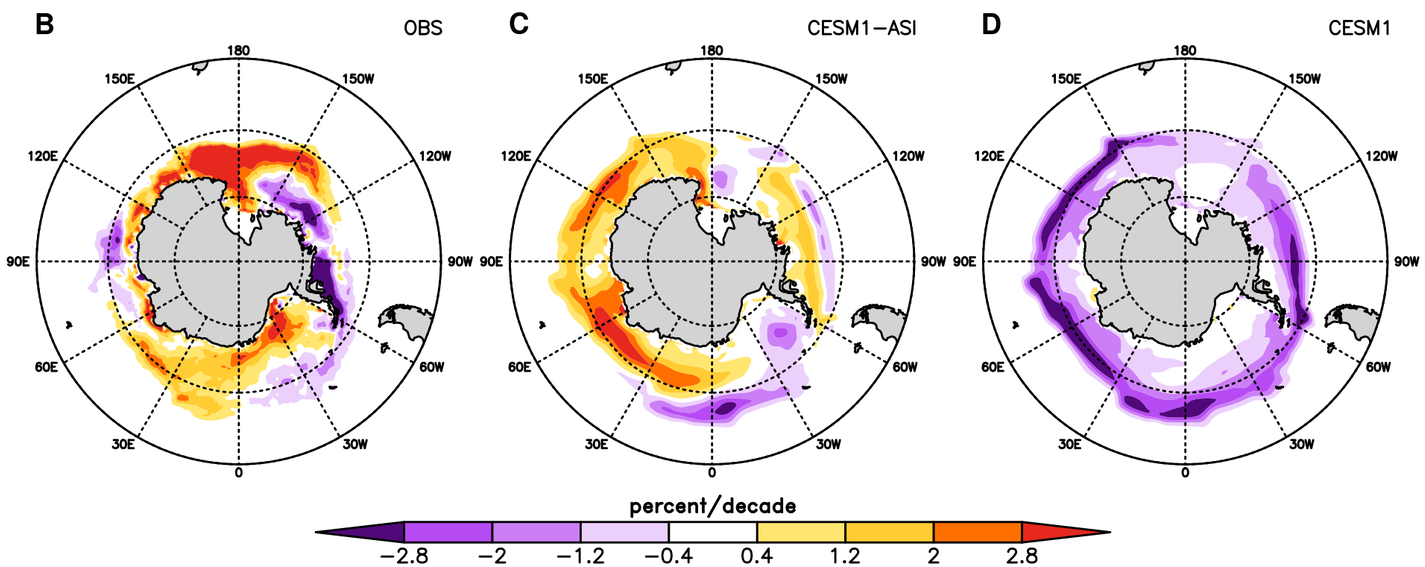
Antarctic sea ice expansion is accompanied by a significant subsurface cooling off the Antarctic coast to about 50°S, mostly in the upper 100 m, and enhanced warming beneath. This is perhaps due to a net northward sea-ice transport that allows freshwater to be extracted near Antarctica and released into the open ocean, intensifying stratification and thus cooling the surface open-ocean waters while reducing vertical mixing to warm the waters beneath. Cooling in the upper-layer waters, in turn, can aid in the expansion of sea ice

Can all of these be proved due to sea ice?

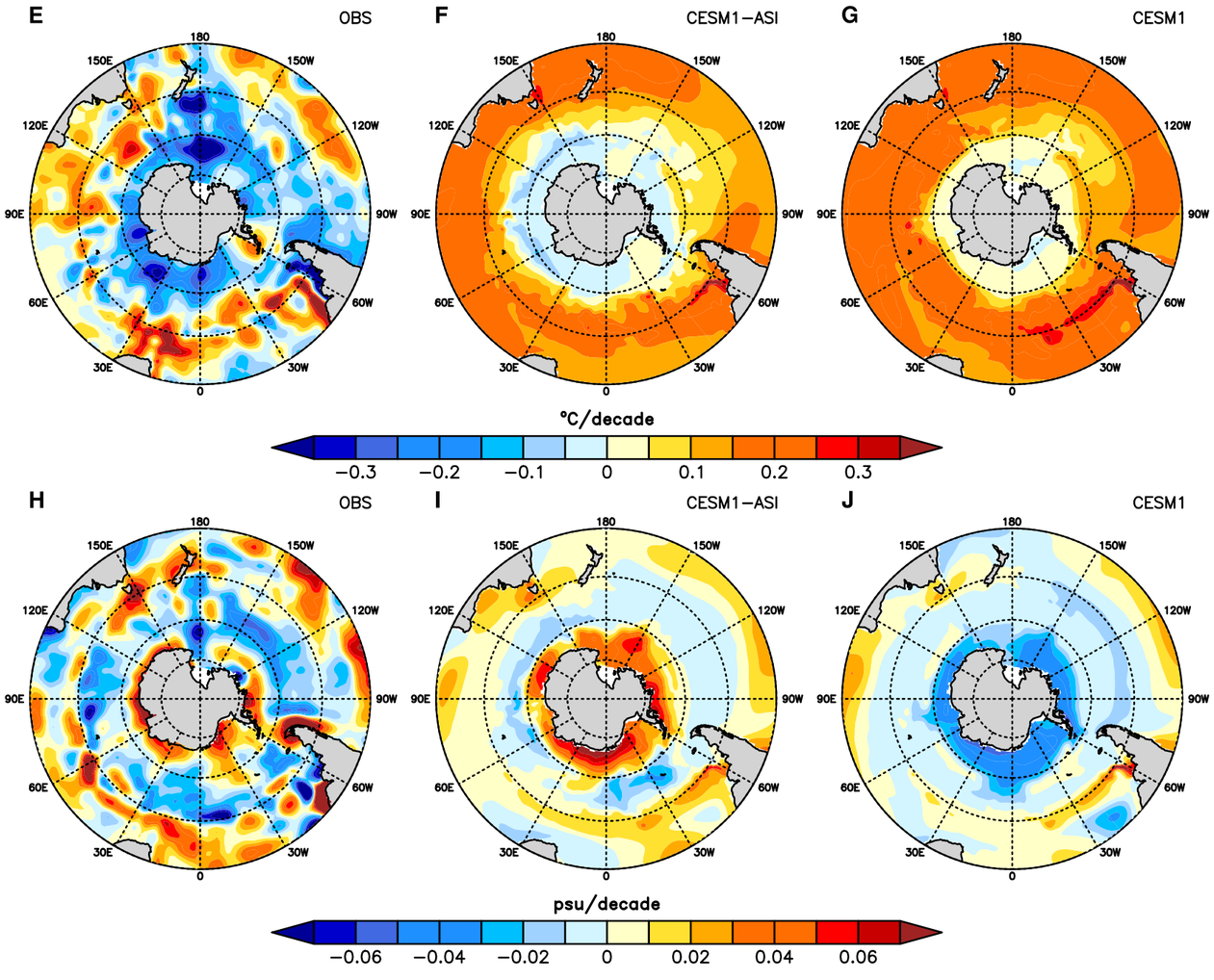


Liu (2025b)

- Increase snow/ice emissivity in CESM1 by a time-evolving factor of [1.2 + (year – 1979) × 0.05] over the Antarctic sea ice area under historical+RCP45 scenario where year denotes the year index
- The 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. 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



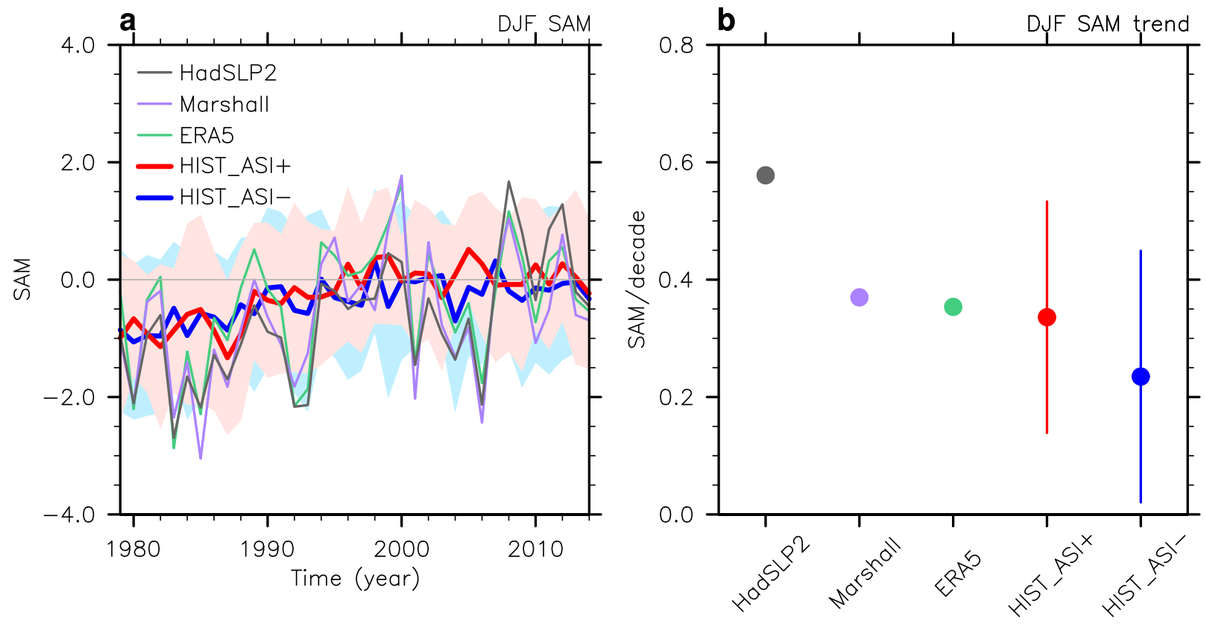
Linked to high-latitude Southern Ocean surface cooling and salinification

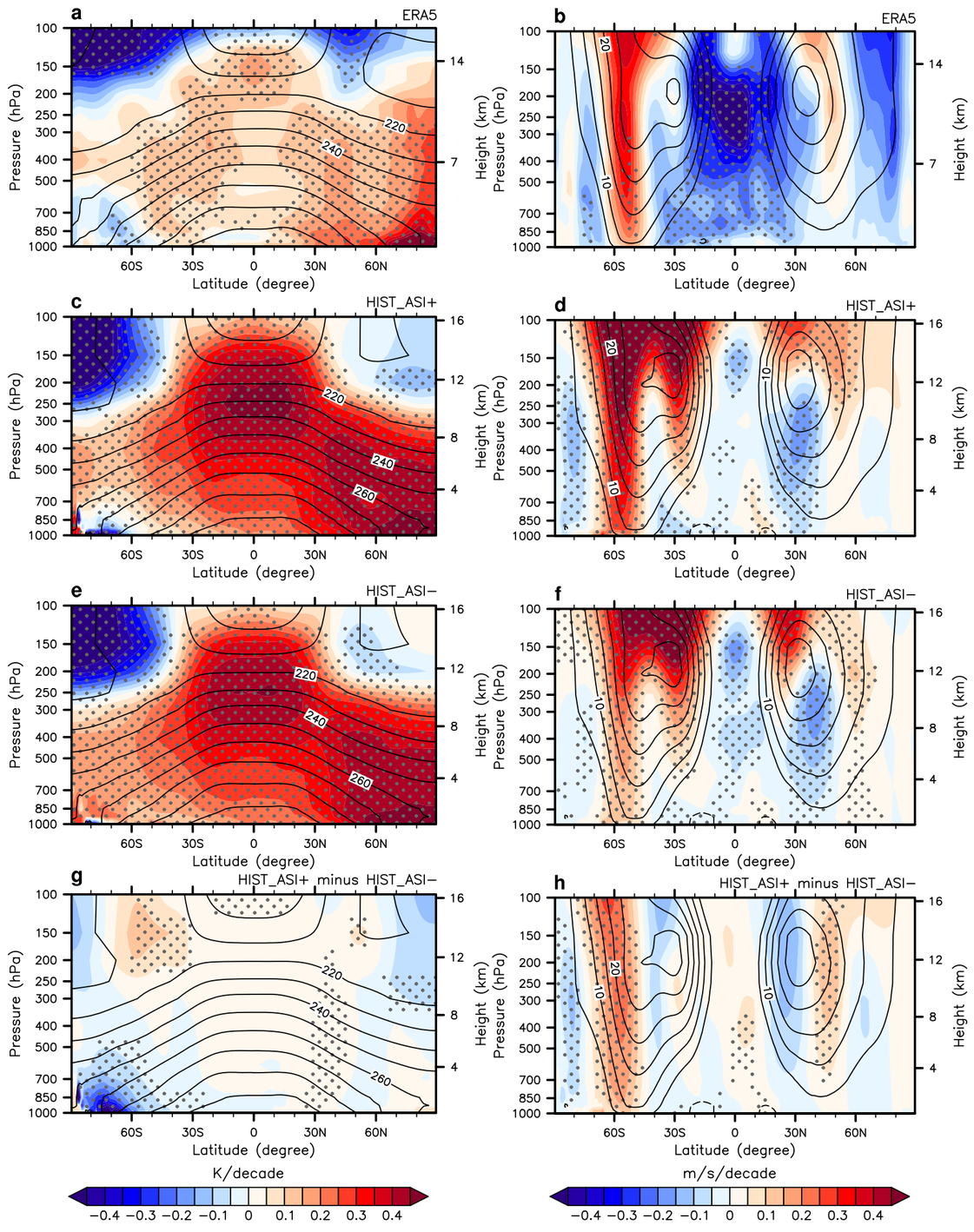


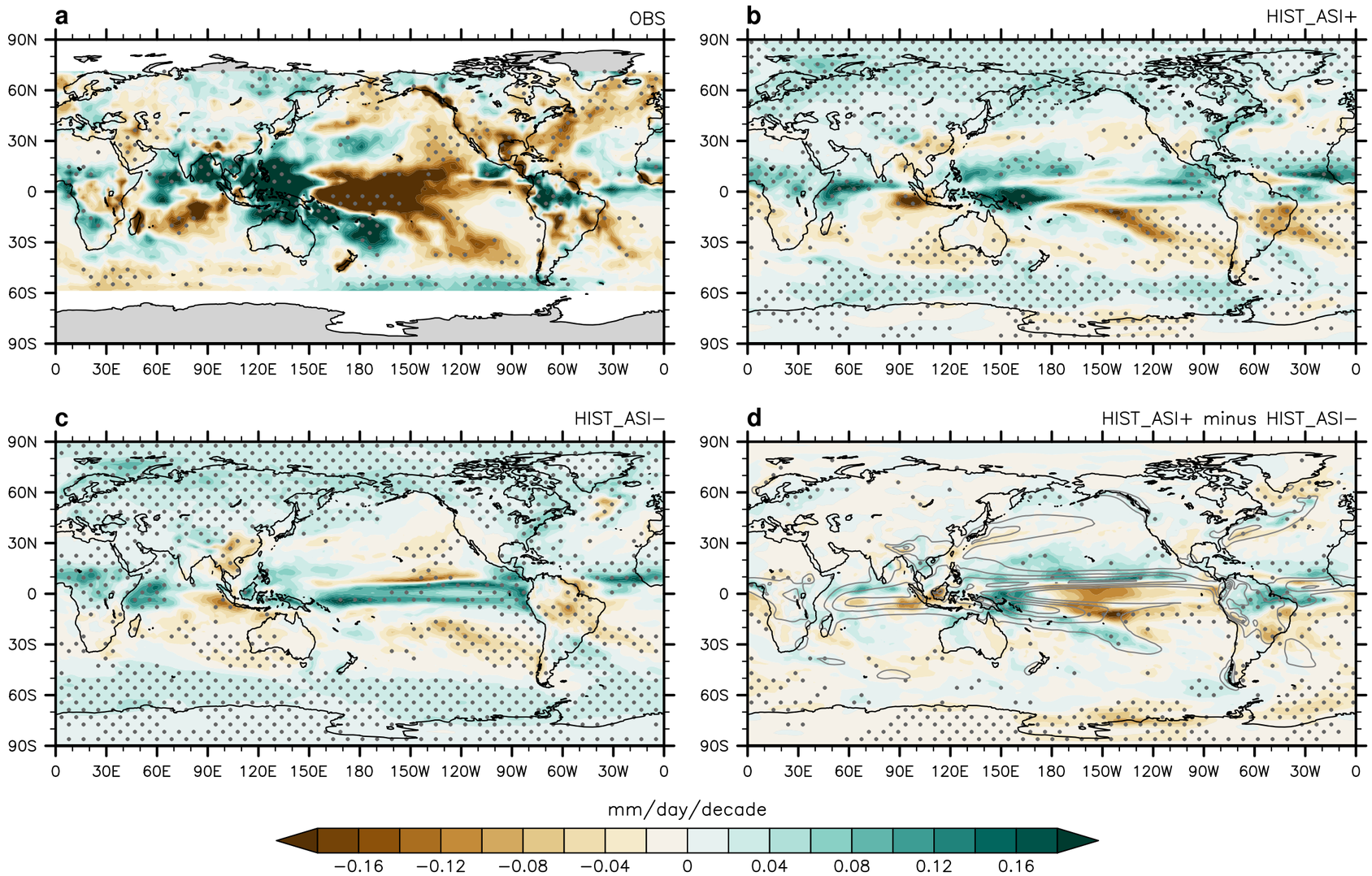
- Antarctic sea ice expansion in CESM1-ASI causes a notable SST cooling primarily south of 60°S in the Southern Ocean
- Antarctic sea ice expansion in CESM1-ASI also brings on a conspicuous increasing trend of surface salinity from the Antarctic coast to 60°S and a surface freshening trend north of 60°S in the Southern Ocean, consistent with observation
- This is because sea ice forms around the Antarctic coast, moves northward due to meridional wind drift, and melts in the open ocean in lower latitudes

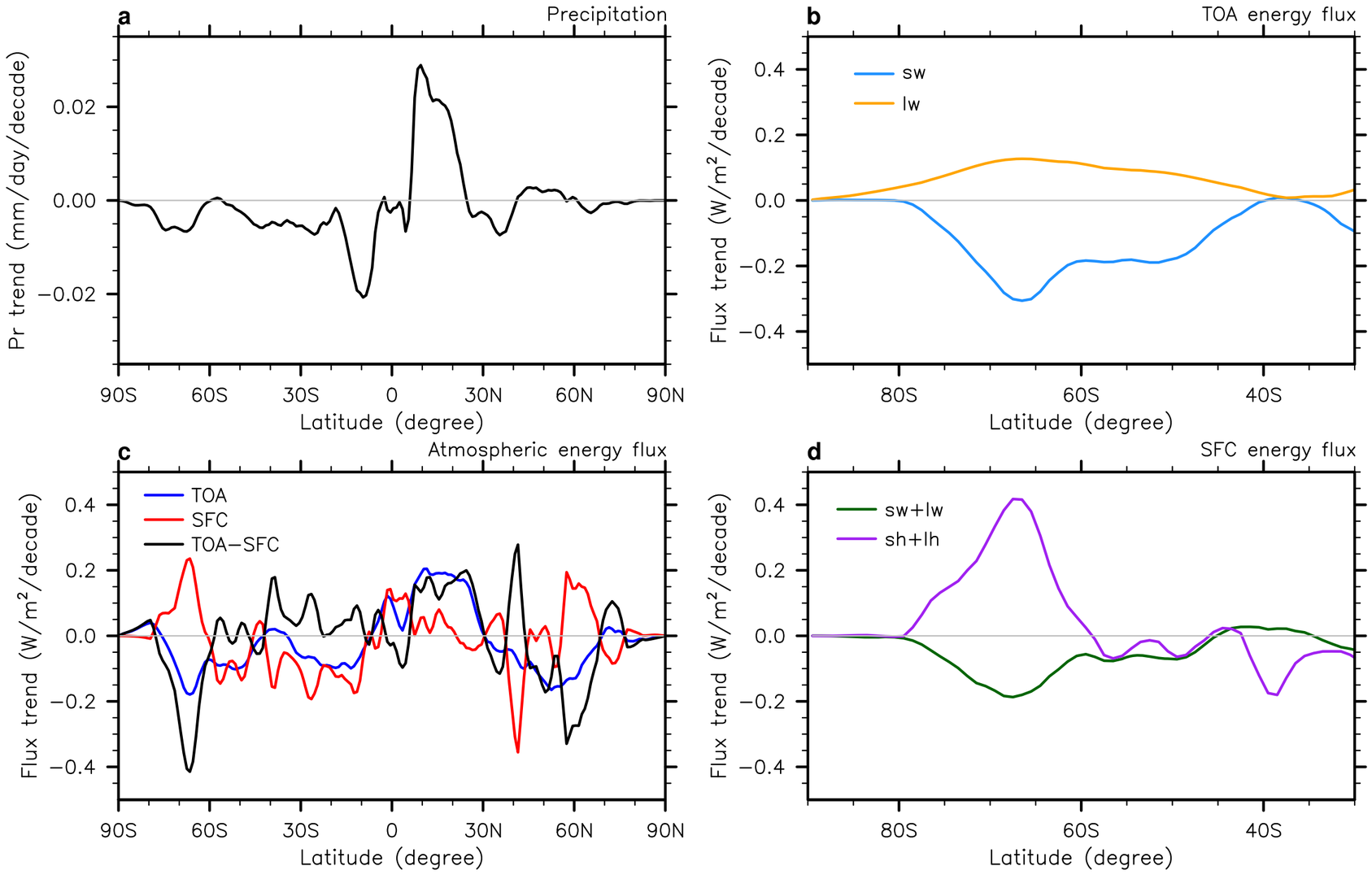
Conclusion

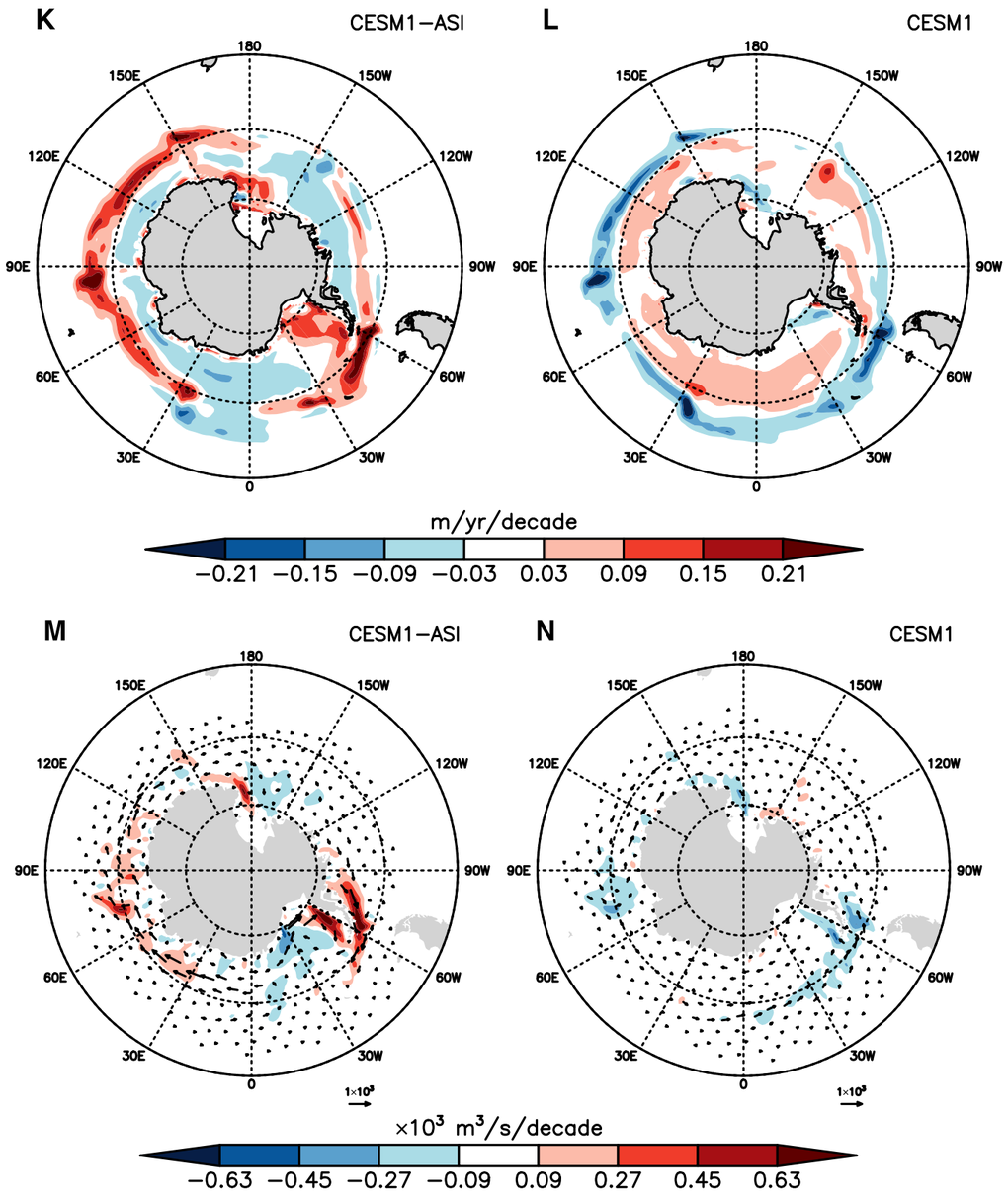
- Historical ensemble simulations with multiple climate models to show that sea-ice natural variability enables the models to simulate an Antarctic sea ice expansion from 1979 to 2014 under anthropogenic forcings. Along with sea-ice expansion, Southern Ocean surface and subsurface temperatures up to 50^{o}S exhibit significant cooling trends, both of which are consistent with observations.
- Neither the Southern Annular Mode nor the Interdecadal Pacific Oscillation can fully explain the simulated Antarctic sea ice expansion over 1979–2014, while the sea-ice expansion is closely linked to surface meridional winds associated with a zonal wave 3 pattern.
- Further Antarctic sea-ice perturbation experiment demonstrates the linkage between Antarctic sea ice expansion and high-latitude Southern Ocean surface cooling and salinification.


a
DJF SAM
HadSLP2
Marshall
ERA5
HIST_ASI+
HIST_ASI−
SAM
4.0
2.0
0.0
−2.0
−4.0
1980
1990
2000
2010
Time (year)
b
DJF SAM trend
SAM/decade
0.8
0.6
0.4
0.2
0.0
HadSLP2
Marshall
ERA5
HIST_ASI+
HIST_ASI−
c
COBESSTv2
ERSSTv5
HadISST
HIST_ASI+
HIST_ASI−
TPI (°C)
0.8
0.4
0.0
−0.4
−0.8
1980
1990
2000
2010
Time (year)


a
ERA5
b
ERA5
c
HIST_ASI+
d
HIST_ASI+
e
HIST_ASI−
f
HIST_ASI−
g
HIST_ASI+ minus HIST_ASI−
h
HIST_ASI+ minus HIST_ASI−
Pressure (hPa)
Height (km)
Latitude (degree)
60S
30S
0
30N
60N
K/decade
m/s/decade
−0.4 −0.3 −0.2 −0.1 0 0.1 0.2 0.3 0.4


a
OBS
b
HIST_ASI+
c
HIST_ASI−
d
HIST_ASI+ minus HIST_ASI−
90N
60N
30N
0
30S
60S
90S
0 30E 60E 90E 120E 150E 180 150W 120W 90W 60W 30W 0
mm/day/decade
−0.16 −0.12 −0.08 −0.04 0 0.04 0.08 0.12 0.16


a
Precipitation
Pr trend (mm/day/decade)
0.02
0.00
−0.02
90S
60S
30S
0
30N
60N
90N
Latitude (degree)
b
TOA energy flux
sw
lw
Flux trend (W/m²/decade)
0.4
0.2
0.0
−0.2
−0.4
80S
60S
40S
Latitude (degree)
c
Atmospheric energy flux
TOA
SFC
TOA−SFC
d
SFC energy flux
sw+lw
sh+lh


K
CESM1−ASI
L
CESM1
180
150E
150W
120E
120W
90E
90W
60E
60W
30E
30W
0
m/yr/decade
−0.21 −0.15 −0.09 −0.03 0.03 0.09 0.15 0.21
M
CESM1−ASI
N
CESM1
1×10³
×10³ m³/s/decade
−0.63 −0.45 −0.27 −0.09 0.09 0.27 0.45 0.63