

Supporting Information for

**Distinct impacts of diverse forcing agents on Arctic sea ice  
since the mid-twentieth century**

Yu-Chi Lee<sup>1\*</sup>, Wei Liu<sup>1</sup>, Clara Deser<sup>2</sup>, and Marika Holland<sup>2</sup>

<sup>1</sup>Department of Earth and Planetary Sciences, University of California Riverside,  
Riverside, CA, 92521, USA.

<sup>2</sup>Climate and Global Dynamics Laboratory, NSF-National Center for Atmospheric  
Research, Boulder, CO, USA

Corresponding author: Yu-Chi Lee ([yuchi.lee@email.ucr.edu](mailto:yuchi.lee@email.ucr.edu))

**Contents of this file**

Tables S1 to S3 and Figures S1 to S14

## Supplementary Tables

**Table S1: CMIP5 and CMIP6 models and their ensemble simulation configurations.** List of CMIP5 and CMIP6 models, simulations and ensemble members used in this study.

<b>Model</b>	<b>CMIP5/6</b>	<b>Historical</b>	<b>GHG-only</b>	<b>AER-only</b>
CCSM4	CMIP5	r[1-6]i1p1	r[1,4,6]i1p1	r[1,4,6]i1p10
CSIRO-Mk3-6-0	CMIP5	r[1-3,5-7,9-10]i1p1	r[1,3-5]i1p1	r[1-5]i1p4
CanESM2	CMIP5	r[1-5]i1p1	r[1-5]i1p1	r[1-5]i1p4
GFDL-CM3	CMIP5	r[1-5]i1p1	r[1,3,5]i1p1	r[1,3,5]i1p1
ACCESS-CM2	CMIP6	r[1-10]i1p1f1	r[1-3]i1p1f1	r[1-3]i1p1f1
ACCESS-ESM1-5	CMIP6	r[1-40]i1p1f1	r[1-3]i1p1f1	r[1-3]i1p1f1
CESM2	CMIP6	r[1-4, 6-7, 9-11]i1p1f1	r1i1p1f1	r[1,3]i1p1f1
CNRM-CM6-1	CMIP6	r[1-20, 29]i1p1f1	r[1-10]i1p1f1	r[1-10]i1p1f1
GFDL-ESM4	CMIP6	r1i1p1f1	r1i1p1f1	r1i1p1f1
IPSL-CM6A-LR	CMIP6	r[1-2, 4-33]i1p1f1	r[1-10]i1p1f1	r[1-10]i1p1f1
MIROC6	CMIP6	r[1-50]i1p1f1	r[1-3]i1p1f1	r[1-3]i1p1f1
MRI-ESM2-0	CMIP6	r[1-6]i1p1f1 & r1i2p1f1	r[1-5]i1p1f1	r[1-5]i1p1f1
NorESM2-LM	CMIP6	r[1-3]i1p1f1 & r1i1p4f1	r[2,3]i1p1f1	r[1-3]i1p1f1

**Table S2: Trends in Arctic sea ice area.** Annual and ensemble-mean linear trends of Arctic sea ice area (SIA) for the periods 1956-1980 and 1981-2005.

(10 <sup>6</sup> km <sup>2</sup> /decade)	Historical	GHG	AAER	BMB
<b>1956-1980</b>				
<b>Walsh et al. (2019)</b>	-0.09	N/A	N/A	N/A
<b>CESM1</b>	-0.02	-0.17*	0.26*	0.04
<b>CMIP5 &amp; 6 MMM</b>	0.02 (3*)	-0.15 (9*)	0.10 (6*)	N/A
<b>1981-2005</b>				
<b>Walsh et al. (2019)</b>	-0.42*	N/A	N/A	N/A
<b>CESM1</b>	-0.20*	-0.29*	-0.16*	0.14*
<b>CMIP5 &amp; 6 MMM</b>	-0.25 (13*)	-0.17 (10*)	-0.06 (5*)	N/A

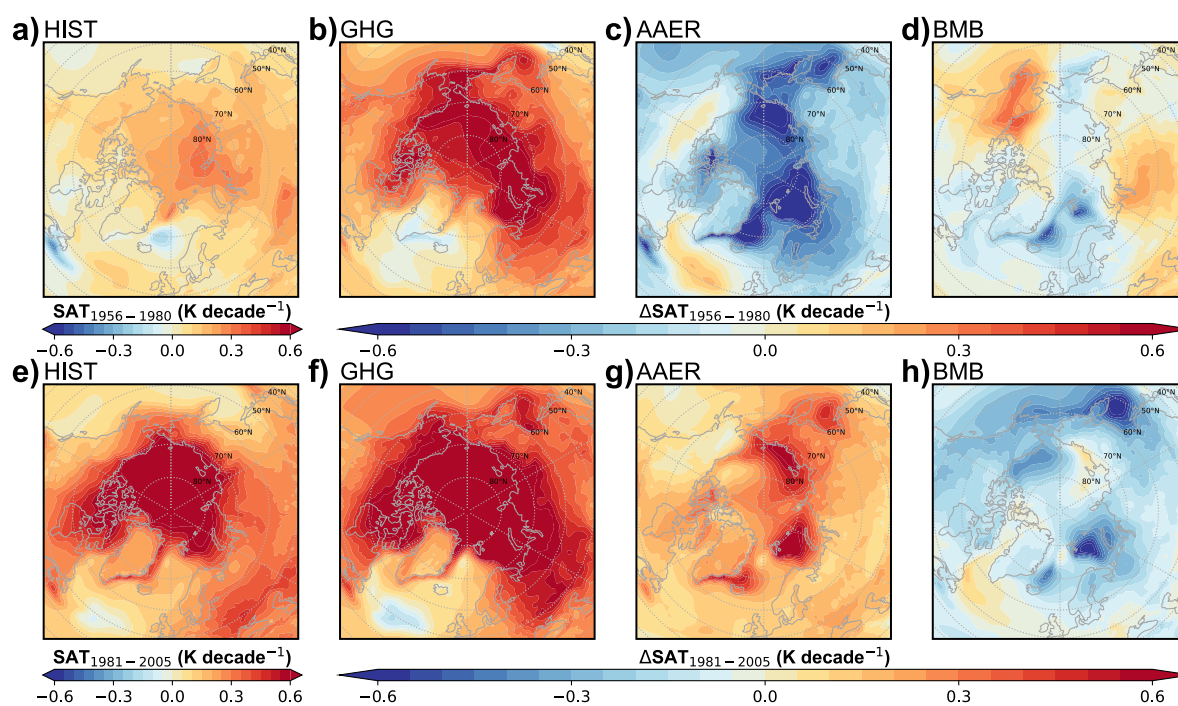
Note: For observations, trend values marked with asterisk (\*) are significant at the 95 % confidence level. In CESM1, asterisk (\*) denotes that the trend of the ensemble-mean time series is significant at 95%. In CMIP5 & 6 multi-model mean (MMM), (n of 13)\* indicates that n out of the 13 individual models exhibit a trend significant at the 95% level with the same sign.

**Table S3: Trends in Arctic sea ice volume.** Annual and ensemble-mean linear trends of Arctic sea ice volume (SIV) for the periods 1956-1980 and 1981-2005.

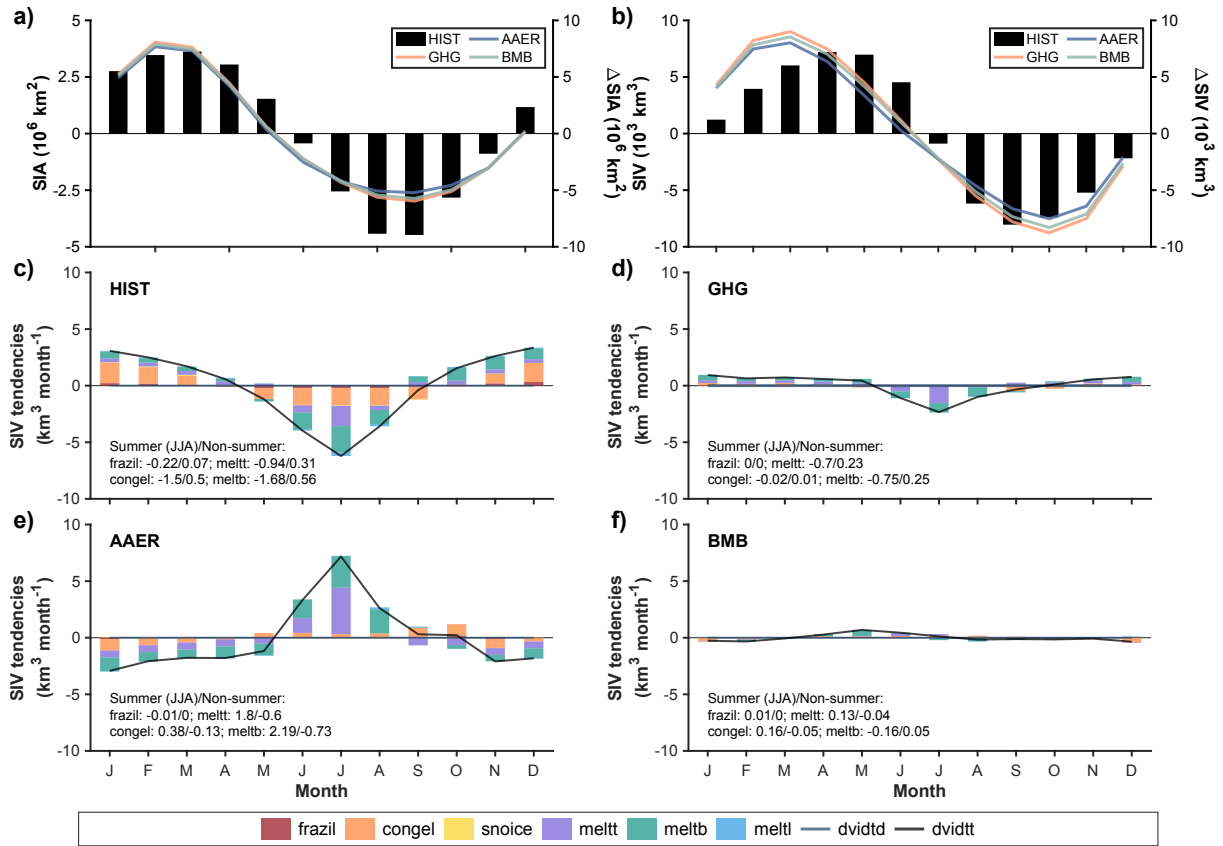
(10 <sup>3</sup> km <sup>3</sup> /decade)	Historical	GHG	AAER	BMB
<b>1956-1980</b>				
<b>CESM1</b>	0.25	-1.30*	2.59*	0.39*
<b>CMIP5 &amp; 6 MMM</b>	0.26 (6*)	-0.59 (10*)	1.26 (9*)	N/A
<b>1981-2005</b>				
<b>CESM1</b>	-2.37*	-3.25*	-1.54*	0.55*
<b>CMIP5 &amp; 6 MMM</b>	-1.63 (13*)	-0.90 (8*)	-0.16 (3*)	N/A

Note: In CESM1, asterisk (\*) denotes that the trend of the ensemble-mean time series is significant at 95%. In CMIP5 & 6 multi-model mean (MMM), (n of 13)\* indicates that n out of the 13 individual models exhibit a trend significant at the 95% level with the same sign.

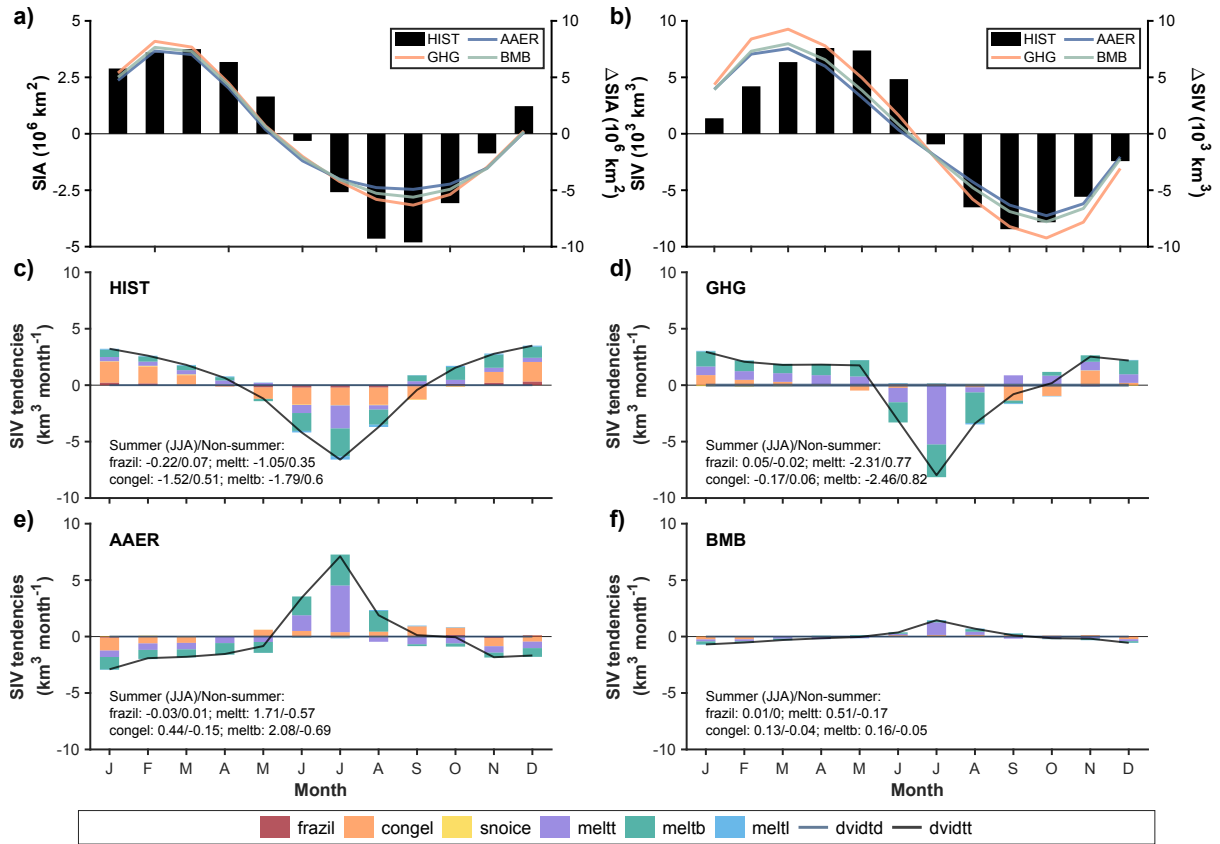
## Supplementary Figures



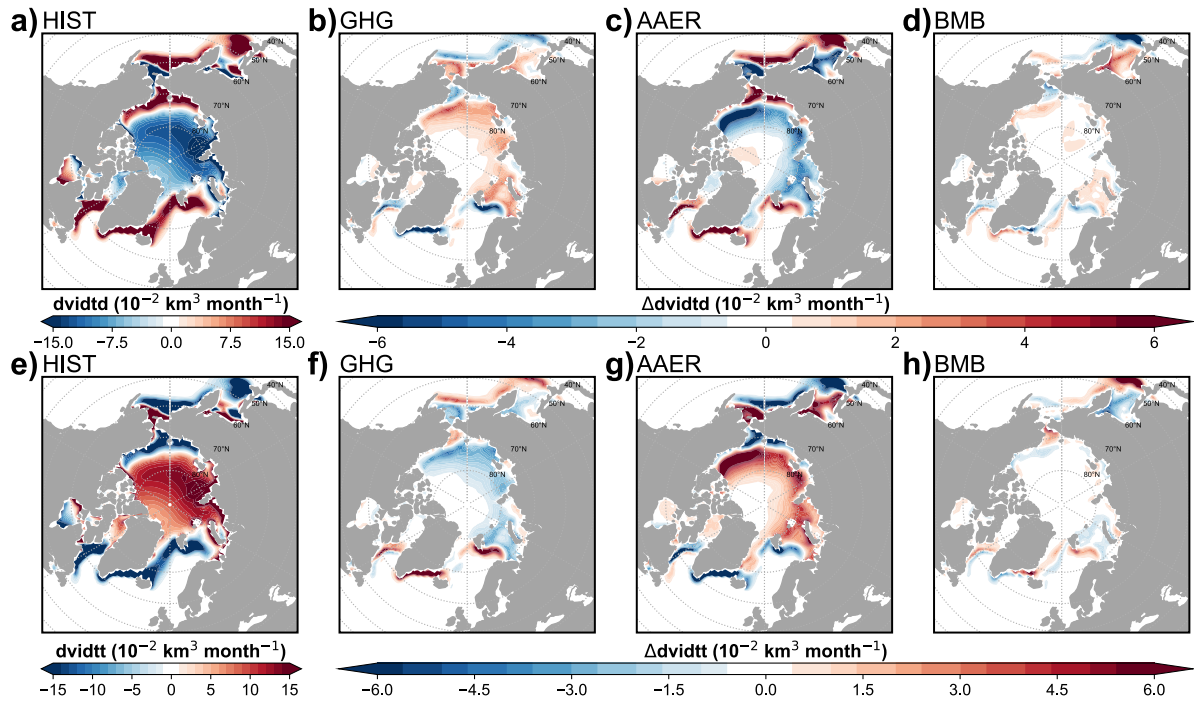
**Fig. S1: Arctic surface air temperature trends during the two periods (1956-1980 and 1981-2005).** Linear trends of annual and ensemble mean surface air temperature (shading in  $\text{K decade}^{-1}$ ) over the Arctic during (a-d) 1956-1980 and (e-h) 1981-2005 under (a,e) historical climate forcings (HIST), only driven by (b,f) well-mixed greenhouse gases (GHGs), (c,g) anthropogenic aerosols (AAER), or (d,h) biomass burning (BMB).



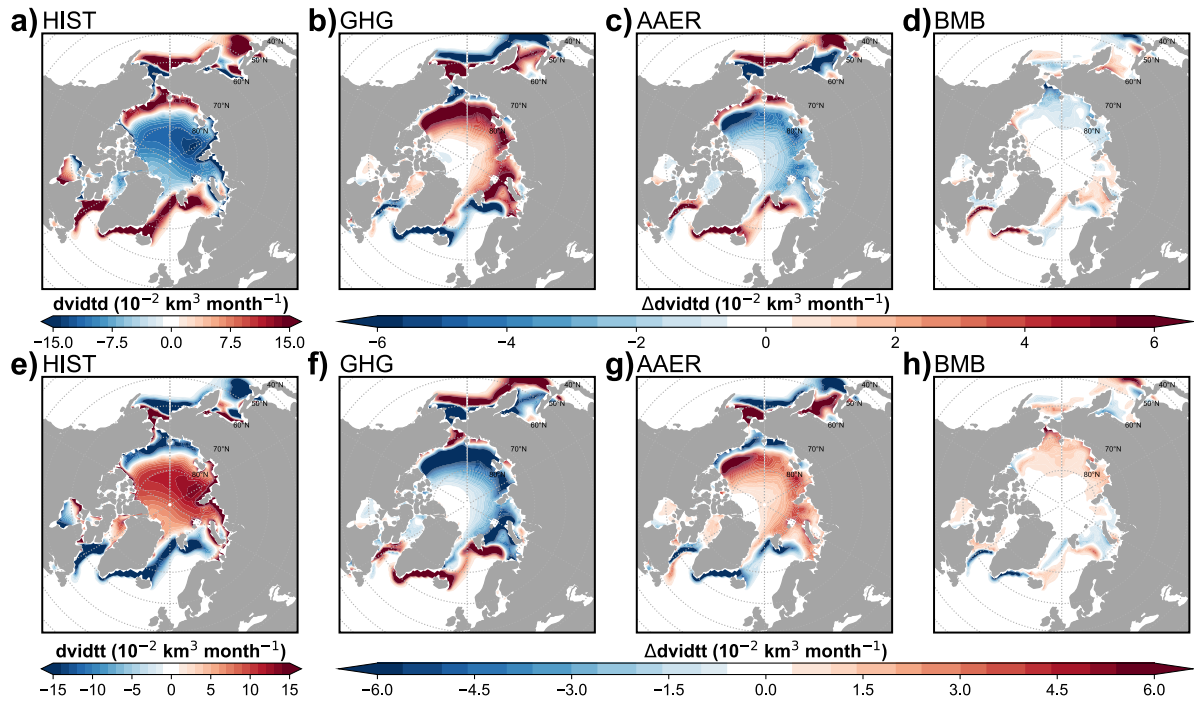
**Fig. S2: Seasonal Arctic sea ice area, volume, and volume budgets over 1956-1980.** Seasonal ensemble-mean Arctic sea ice (a) area and (b) volume as well as (c-f) sea ice volume budget over 1956-1980, with annual mean removed. The left y-axis in (a,b) refers to historical values (HIST: black bars) and the right y-axis refers to contributions from well-mixed greenhouse gases (GHGs: orange lines), anthropogenic aerosols (AAER: blue lines), and biomass burning (BMB: green lines). Panels (c-f) display the budget terms under HIST, GHG, AAER and BMB forcings.



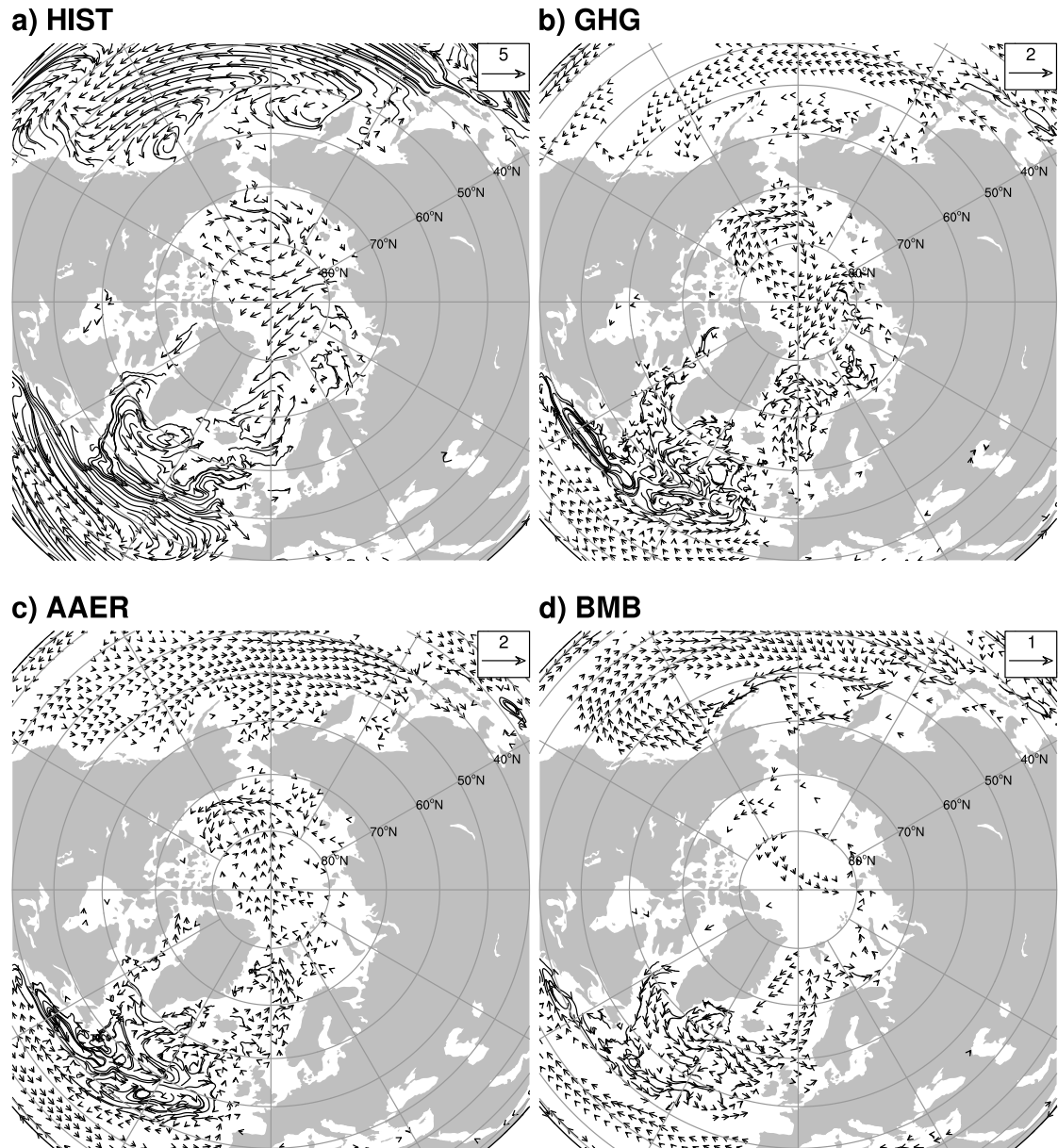
**Fig. S3: Seasonal Arctic sea ice area, volume, and volume budgets over 1981-2005.** Seasonal ensemble-mean Arctic sea ice (a) area and (b) volume as well as (c-f) sea ice volume budget over 1981-2005, with annual mean removed. The left y-axis in (a,b) refers to historical values (HIST: black bars) and the right y-axis refers to contributions from well-mixed greenhouse gases (GHGs: orange lines), anthropogenic aerosols (AAER: blue lines), and biomass burning (BMB: green lines). Panels (c-f) display the budget terms under HIST, GHG, AAER and BMB forcings.



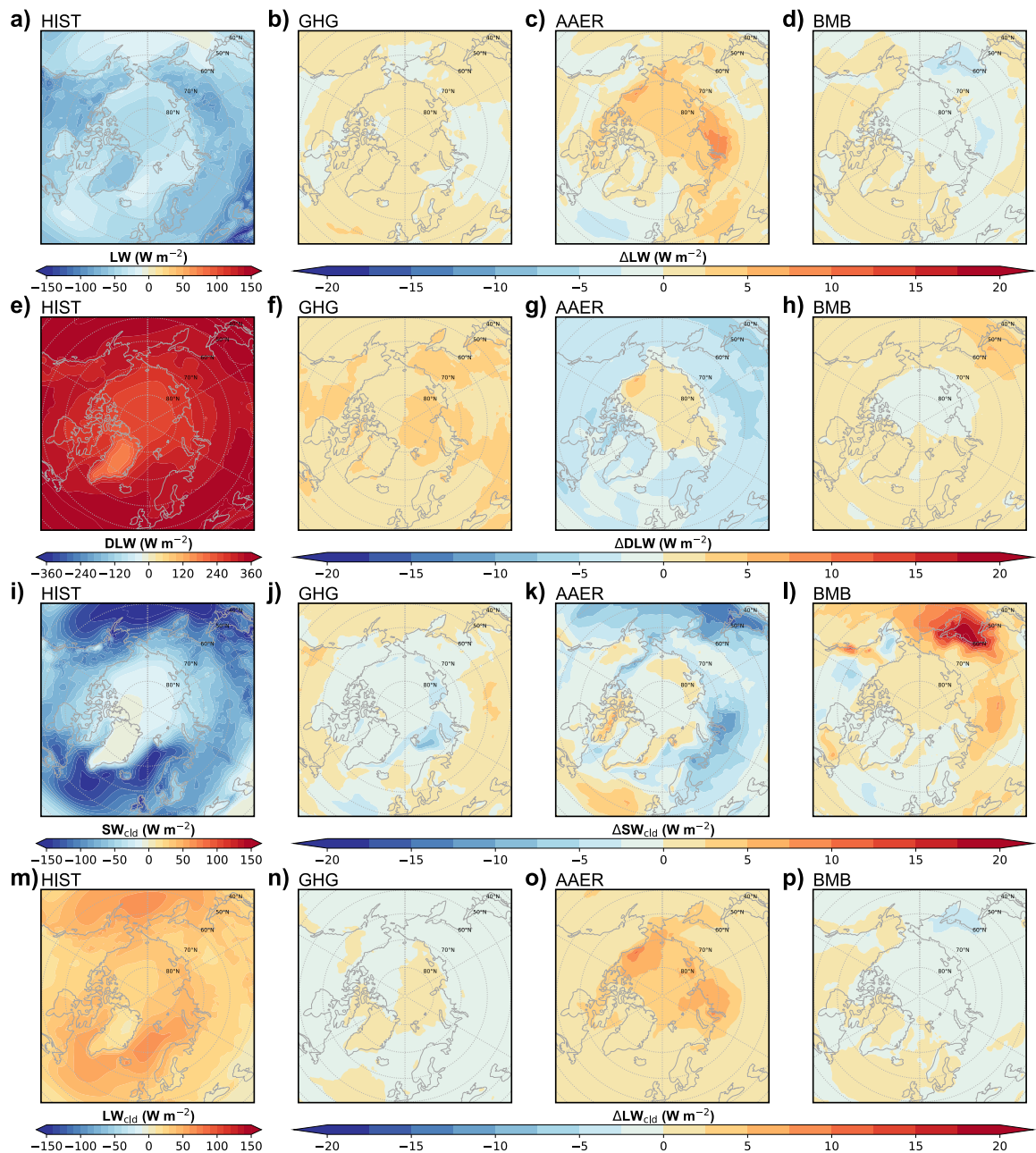
**Fig S4: Annual mean Arctic sea ice volume tendencies (1956-1980) in CESM1.** Annual ensemble mean of (a-d) dynamic sea ice volume tendencies (shading in  $10^{-2} \text{ km}^3 \text{ month}^{-1}$ ) and (e-h) thermodynamic sea ice volume tendencies (shading in  $10^{-2} \text{ km}^3 \text{ month}^{-1}$ ) for the period 1956-1980 under (a,e) historical climate forcings (HIST), only driven by (b,f) well-mixed greenhouse gases (GHGs), (c,g) anthropogenic aerosols (AAER), or (d,h) biomass burning (BMB).



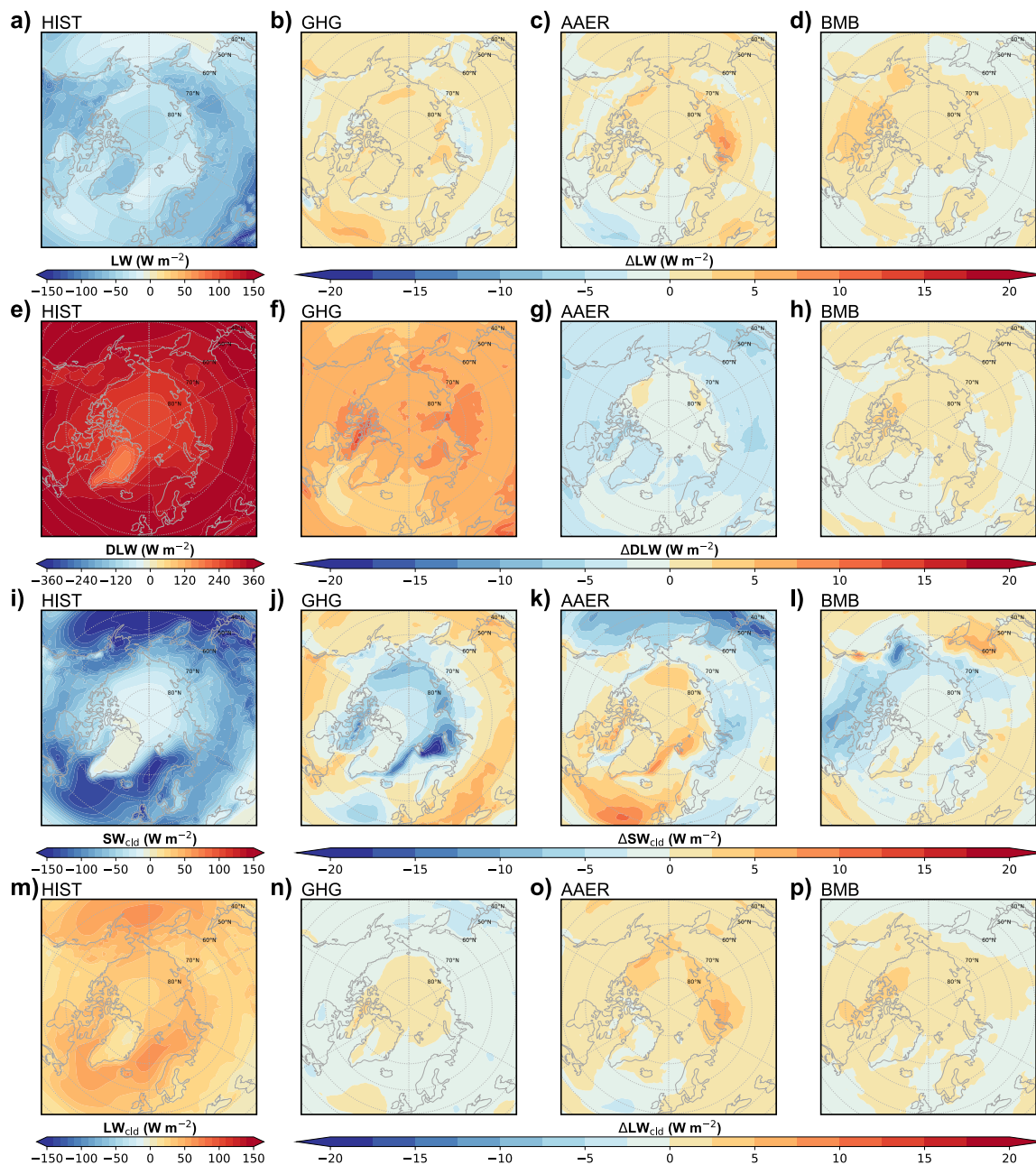
**Fig S5: Annual mean Arctic sea ice volume tendencies (1981-2005) in CESM1.** Annual ensemble mean of (a-d) dynamic sea ice volume tendencies (shading in  $10^{-2} \text{ km}^3 \text{ month}^{-1}$ ) and (e-h) thermodynamic sea ice volume tendencies (shading in  $10^{-2} \text{ km}^3 \text{ month}^{-1}$ ) for the period 1981-2005 under (a,e) historical climate forcings (HIST), only driven by (b,f) well-mixed greenhouse gases (GHGs), (c,g) anthropogenic aerosols (AAER), or (d,h) biomass burning (BMB).



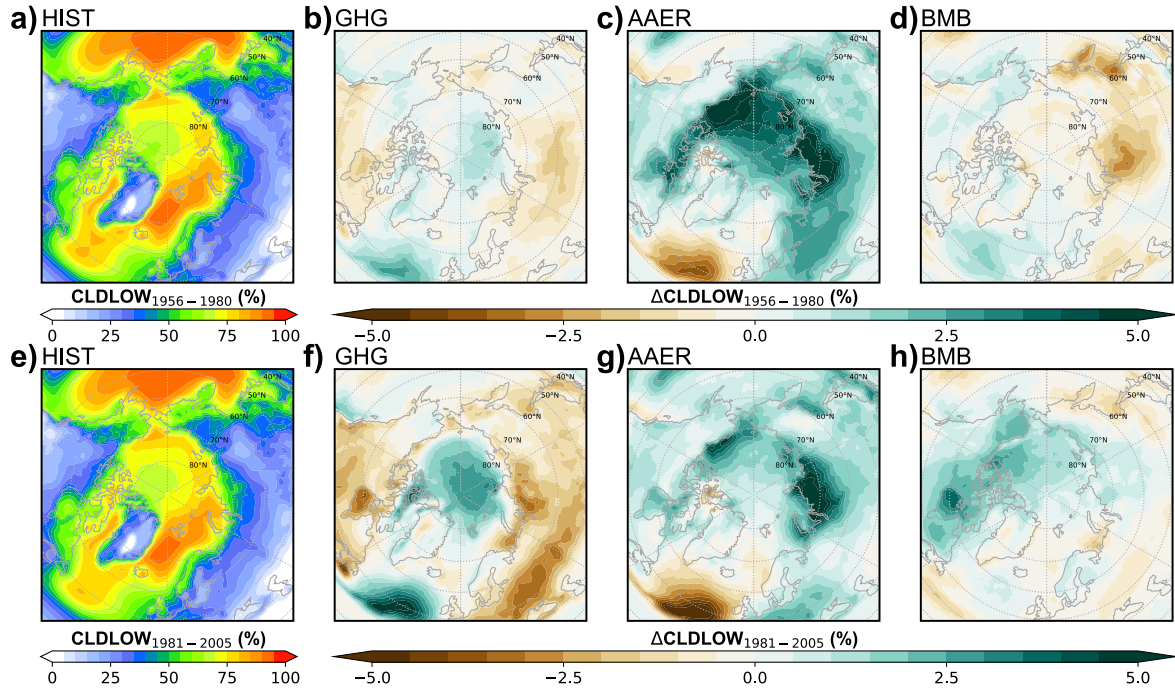
**Fig S6: Surface Ocean current change under different forcing agents in CESM1.** Annual mean surface ocean current (vectors in  $\text{cm s}^{-1}$ ) changes for 1981-2005 under (a) historical climate forcings (HIST) and the contributions from (b) well-mixed greenhouse gases (GHGs), (c) anthropogenic aerosols (AAER), and (d) biomass burning (BMB). The reference vectors in (a-d) represent  $5 \text{ cm s}^{-1}$ ,  $2 \text{ cm s}^{-1}$ ,  $2 \text{ cm s}^{-1}$  and  $1 \text{ cm s}^{-1}$ , respectively. For clarity, vectors with magnitude that is smaller than  $0.1 \text{ cm s}^{-1}$  in (a) and  $0.08 \text{ cm s}^{-1}$  in (b-d) are omitted.



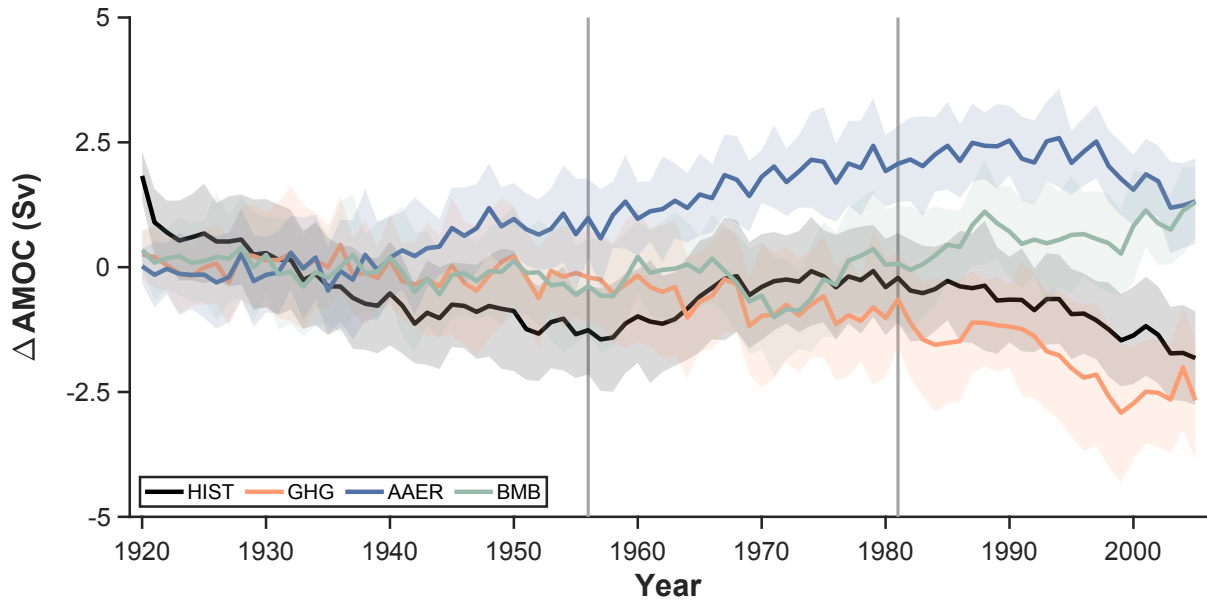
**Fig S7: Summer surface radiation fluxes (1956-1980) under different forcing agents in CESM1.** Boreal summer (JJA) ensemble mean of (a-d) net longwave radiation flux (positive downward, shading in  $\text{W m}^{-2}$ ) for the period 1956-1980 under (a) historical climate forcings (HIST), only driven by (b) well-mixed greenhouse gases (GHGs), (c) anthropogenic aerosols (AAER), or (d) biomass burning (BMB). Same as (a-d) but for (e-h) downward longwave radiation flux, (i-l) cloud-induced shortwave radiation flux, and (m-p) cloud-induced longwave radiation flux.



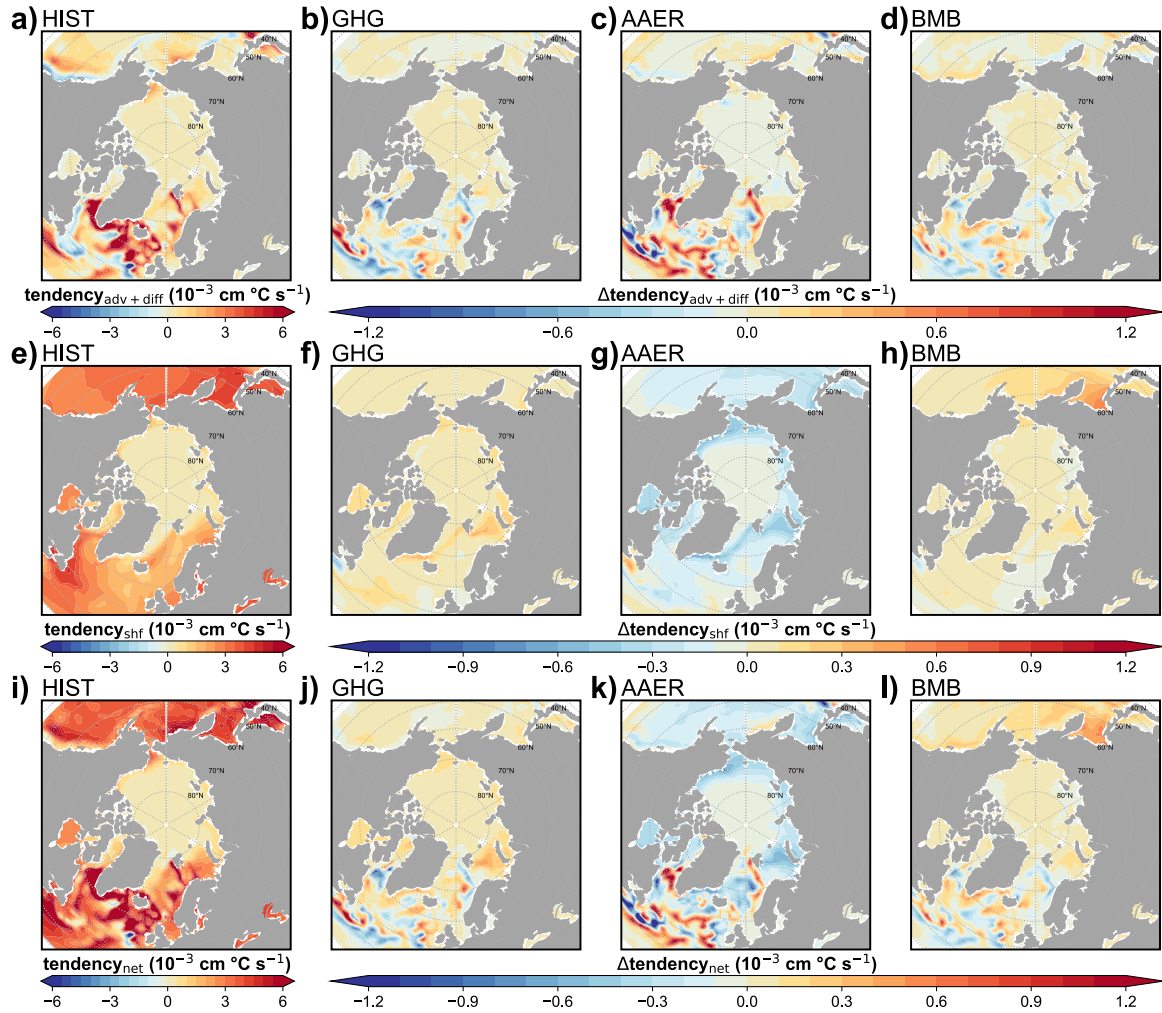
**Fig S8: Summer surface radiation fluxes (1981-2005) under different forcing agents in CESM1.** Boreal summer (JJA) ensemble mean of (a-d) net longwave radiation flux (positive downward, shading in  $\text{W m}^{-2}$ ) for the period 1981-2005 under (a) historical climate forcings (HIST), only driven by (b) well-mixed greenhouse gases (GHGs), (c) anthropogenic aerosols (AAER), or (d) biomass burning (BMB). Same as (a-d) but for (e-h) downward longwave radiation flux, (i-l) cloud-induced shortwave radiation flux, and (m-p) cloud-induced longwave radiation flux.



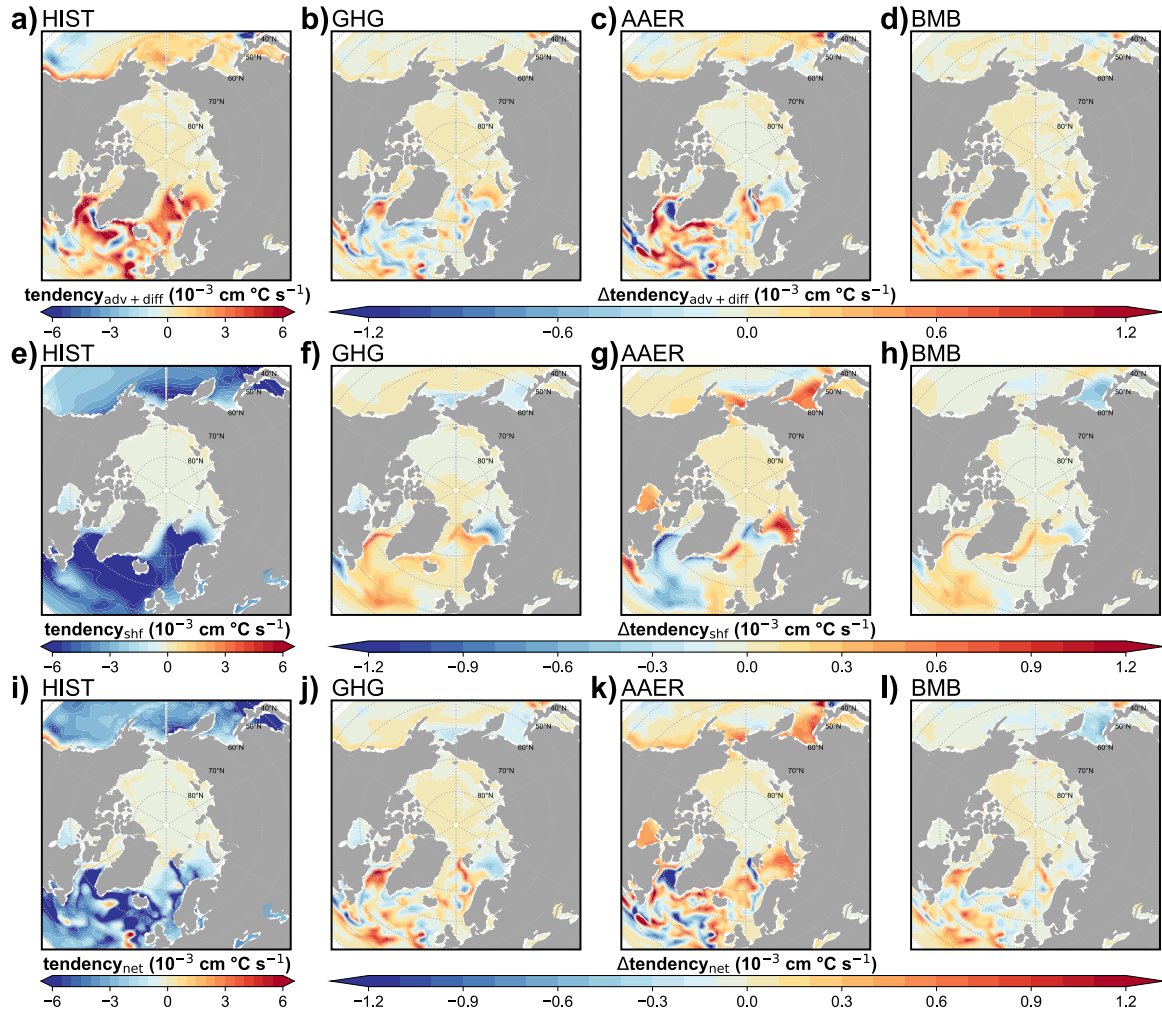
**Fig S9: Summer low-level cloud fraction under different forcing agents in CESM1.** Boreal summer (JJA) ensemble mean of (a-d) low-level cloud fraction (shading in %) for the period 1956-1980 under (a) historical climate forcings (HIST), only driven by (b) well-mixed greenhouse gases (GHGs), (c) anthropogenic aerosols (AAER), or (d) biomass burning (BMB). (e-h) are the same as (a-d) but for the period 1981-2005.



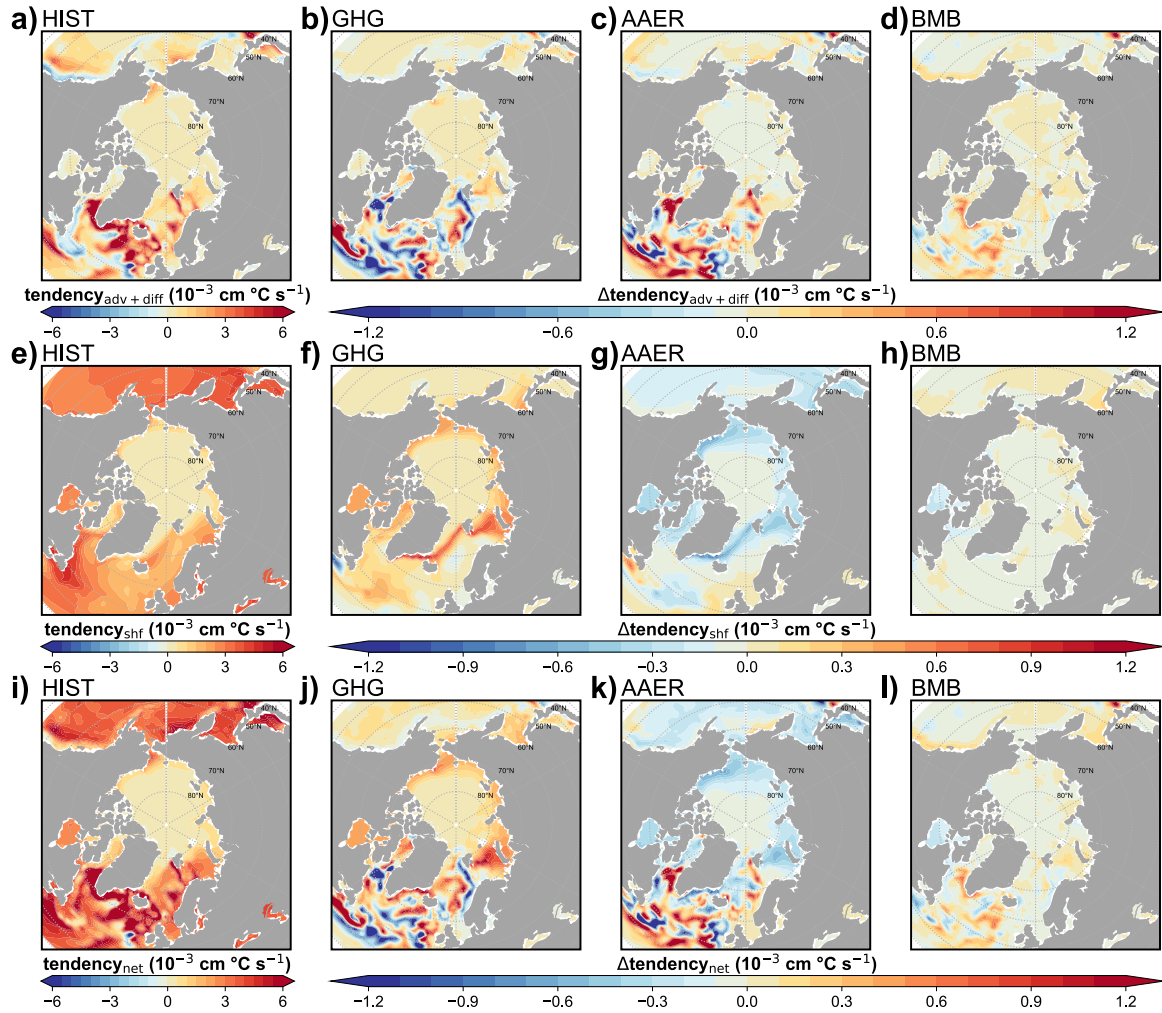
**Fig S10: AMOC changes driven by different climate forcings in CESM1.** Changes in annual and ensemble mean AMOC strength (relative to 1920-1945) under different forcings: historical climate forcings (HIST: black), well-mixed greenhouse gases (GHGs: orange), anthropogenic aerosols (AAER: blue), and biomass burning (BMB: green). Shadings represent one standard deviation across ensemble members. AMOC strength is defined as the maximum of the annual mean stream-function below 500 meters across the North Atlantic.



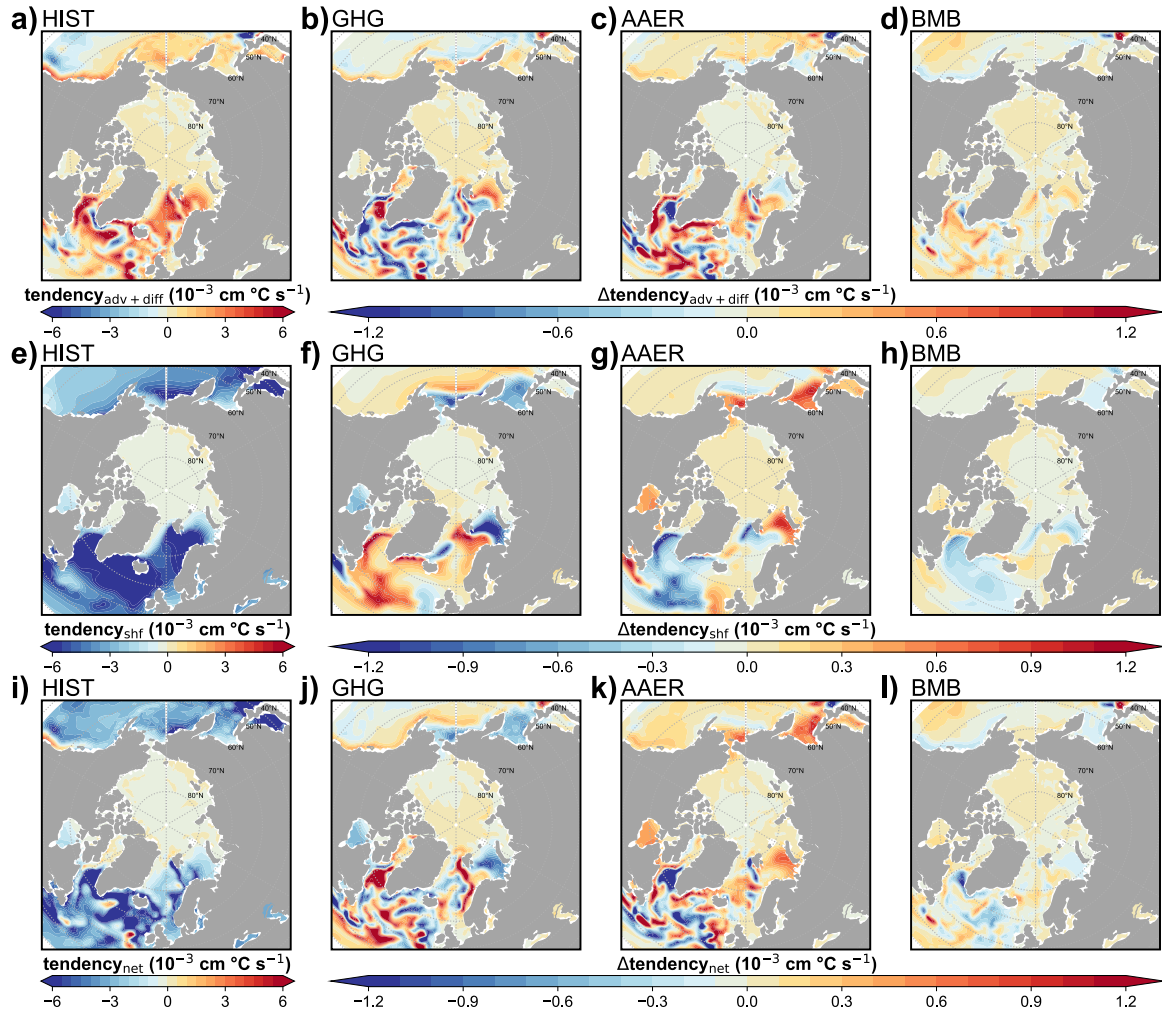
**Fig S11: Summertime ocean temperature changes (1956-1980) induced by different forcing agents in CESM1.** Boreal summer (JJA) and ensemble mean of whole-depth ocean temperature tendencies induced by (a-d) advection and diffusion processes (shading in  $10^{-3} \text{ cm } ^\circ\text{C s}^{-1}$ ), (e-h) surface heat fluxes, and (i-l) net tendencies (a-d plus e-h, respectively) for the period 1956-1980 under (a,e,i) historical climate forcings (HIST), only driven by (b,f,j) well-mixed greenhouse gases (GHGs), (c,g,k) anthropogenic aerosols (AAER), or (d,h,l) biomass burning (BMB).



**Fig S12: Wintertime ocean temperature changes (1956-1980) induced by different forcing agents in CESM1.** Boreal winter (DJF) and ensemble mean of whole-depth ocean temperature tendencies induced by (a-d) advection and diffusion processes (shading in  $10^{-3} \text{ cm } ^\circ\text{C s}^{-1}$ ), (e-h) surface heat fluxes, and (i-l) net tendencies (a-d plus e-h, respectively) for the period 1956-1980 under (a,e,i) historical climate forcings (HIST), only driven by (b,f,j) well-mixed greenhouse gases (GHGs), (c,g,k) anthropogenic aerosols (AAER), or (d,h,l) biomass burning (BMB).



**Fig S13: Summertime ocean temperature changes (1981-2005) induced by different forcing agents in CESM1.** Boreal summer (JJA) and ensemble mean of whole-depth ocean temperature tendencies induced by (a-d) advection and diffusion processes (shading in  $10^{-3} \text{ cm } ^\circ\text{C s}^{-1}$ ), (e-h) surface heat fluxes, and (i-l) net tendencies (a-d plus e-h, respectively) for the period 1981-2005 under (a,e,i) historical climate forcings (HIST), only driven by (b,f,j) well-mixed greenhouse gases (GHGs), (c,g,k) anthropogenic aerosols (AAER), or (d,h,l) for biomass burning (BMB).



**Fig S14: Wintertime ocean temperature changes (1981-2005) induced by different forcing agents in CESM1.** Boreal winter (DJF) and ensemble mean of whole-depth ocean temperature tendencies induced by (a-d) advection and diffusion processes (shading in  $10^{-3} \text{ cm } ^\circ\text{C s}^{-1}$ ), (e-h) surface heat fluxes, and (i-l) net tendencies (a-d plus e-h, respectively) for the period 1981-2005 under (a,e,i) for historical climate forcings (HIST), only driven by (b,f,j) well-mixed greenhouse gases (GHGs), (c,g,k) anthropogenic aerosols (AAER), or (d,h,l) biomass burning (BMB).