Supplementary Information for "Stronger Arctic Amplification Produced by Anthropogenic Aerosols than by Greenhouse Gases"

You-Ting Wu[1], Yu-Chiao Liang[1*], Michael Previdi[2], Lorenzo M. Polvani[2,3,4], Mark R. England[5], Michael Sigmond[6], and Min-Hui Lo[1]

[1]Department of Atmospheric Sciences, National Taiwan University, Taipei, Taiwan

[2]Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY, USA

[3]Department of Earth and Environmental Sciences, Columbia University, New York, NY, USA

[4]Department of Applied Physics and Applied Mathematics, Columbia University, New York, NY, USA

[5]Department of Mathematics and Statistics, University of Exeter, Exeter, UK

[6]Canadian Centre for Climate Modelling and Analysis, Environment and Climate Change Canada, Victoria, BC, Canada

[*]e-mail: pamip.yuchiao@gmail.com, yuchiaoliang@ntu.edu.tw

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Energy budget analysis

To understand what is causing Arctic Amplification under different forcing agents, we analyze the energy budget at the top of the atmosphere (TOA) using DAMIP. The budget is formulated as:

$$\Delta F + \lambda \Delta T_s + \Delta SHF + \Delta AHT = 0, \quad (1)$$

where F is the effective radiative forcing (ERF), λ is the feedback parameter, T_s is the surface air temperature, SHF is the net upward surface heat flux, and AHT is the atmospheric heat transport. We define Δ as the trend of given values from 1955-1984 under AER and GHG forcings respectively, and the units of each term are $\mathrm{Wm^{-2}K^{-1}}$.

The ERF could be determined by the net TOA radiation response in the fixed SST simulations[1]. The feedback parameter, λ, could be estimated as the slope of the regrssion line utilized by regressing yearly values of net TOA radiation (R) related to T_s[2]. Using the estimates of ΔF and $\lambda \Delta T_s$, we can calculate ΔAHT as the residual term in equation 1.

Alternatively, $\lambda \Delta T_s$ can be estimated by considering the slow response of R through the equation:

$$\Delta R = \Delta F + \lambda \Delta T_s, \quad (2)$$

where R is decomposed into the fast responses (i.e., ERF) and the slow response (i.e., radiative feedback) of the climate system. With the model output of ΔR and ΔF, we can examine the entire term $\lambda \Delta T_s$ as the residual.

Climate feedback analysis

To examine the local processes contributing to Arctic Amplification under various forcing agents, we employ radiative kernels[3,4] to break down $\lambda \Delta T_s$, resulting in:

$$\Sigma \lambda \Delta T_s = \lambda_{ALB} \Delta T_s + \lambda_{PL} \Delta T_s + \lambda_{LR} \Delta T_s + \lambda_{WV} \Delta T_s + \lambda_{SWC} \Delta T_s + \lambda_{LWC} \Delta T_s. \quad (3)$$

Here, the feedback parameters are categorized into surface albedo (λ_{ALB}), Planck (λ_{PL}), lapse-rate (λ_{LR}), water vapor (λ_{WV}), shortwave cloud (λ_{SWC}), and longwave cloud (λ_{LWC}) feedbacks. Note that we only utilize CESM1 due to a lack of data.

Atmospheric heat transport

To explore the distant mechanisms influencing Arctic Amplification under different forcing agents, we decompose ΔAHT into dry and moisture components:

$$\Delta AHT = \Delta AHT_{DSE} + \Delta AHT_{MSE}, \tag{4}$$

where ΔAHT_{DSE} represents the flux convergence of dry static energy, while ΔAHT_{MSE} is represents moisture static energy flux convergence. For ΔAHT_{MSE}, we estimate it as:

$$\Delta AHT_{MSE} = \Delta P - \Delta E, \tag{5}$$

where P and E denote surface precipitation and evaporation, respectively, with atmospheric moisture storage being disregarded. Thus, ΔAHT_{DSE} is calculated as the difference between ΔAHT and ΔAHT_{MSE}.

References

1. Smith, C. J. *et al.* Effective radiative forcing and adjustments in cmip6 models. *Atmospheric Chem. Phys.* **20**, 9591–9618 (2020).

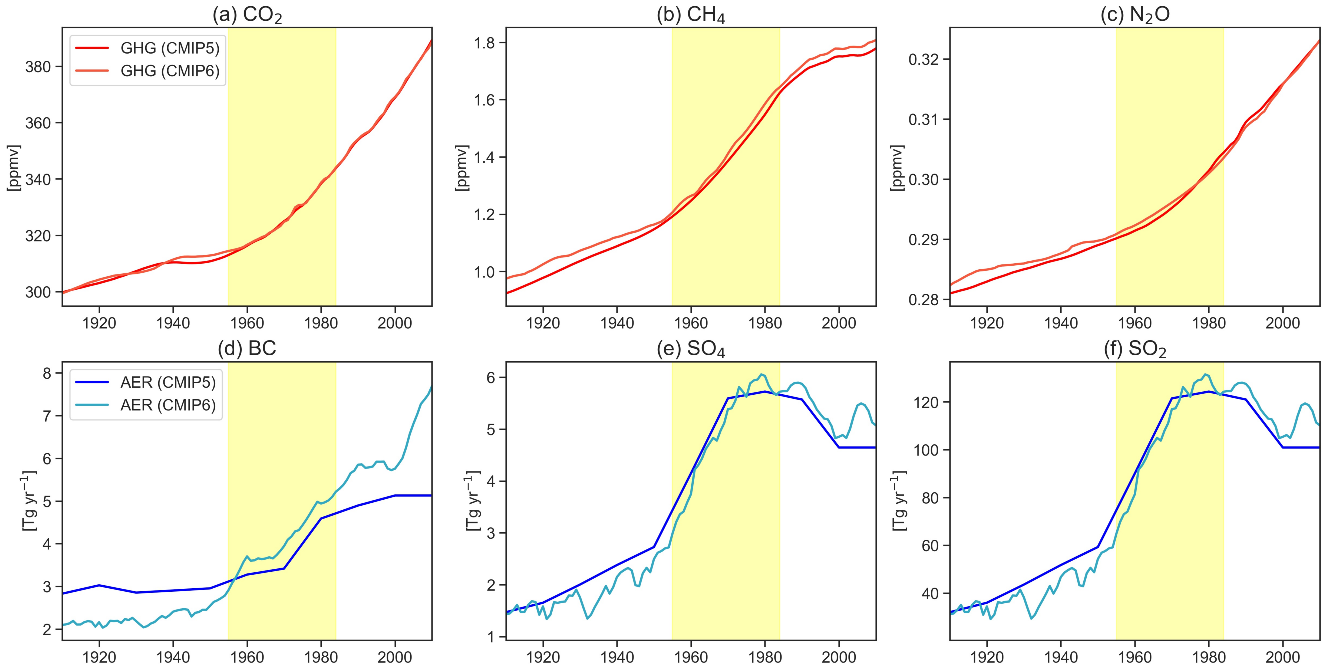
2. Gregory, J. *et al.* A new method for diagnosing radiative forcing and climate sensitivity. *Geophys. research letters* **31** (2004).

3. Soden, B. J. *et al.* Quantifying climate feedbacks using radiative kernels. *J. Clim.* **21**, 3504–3520 (2008).

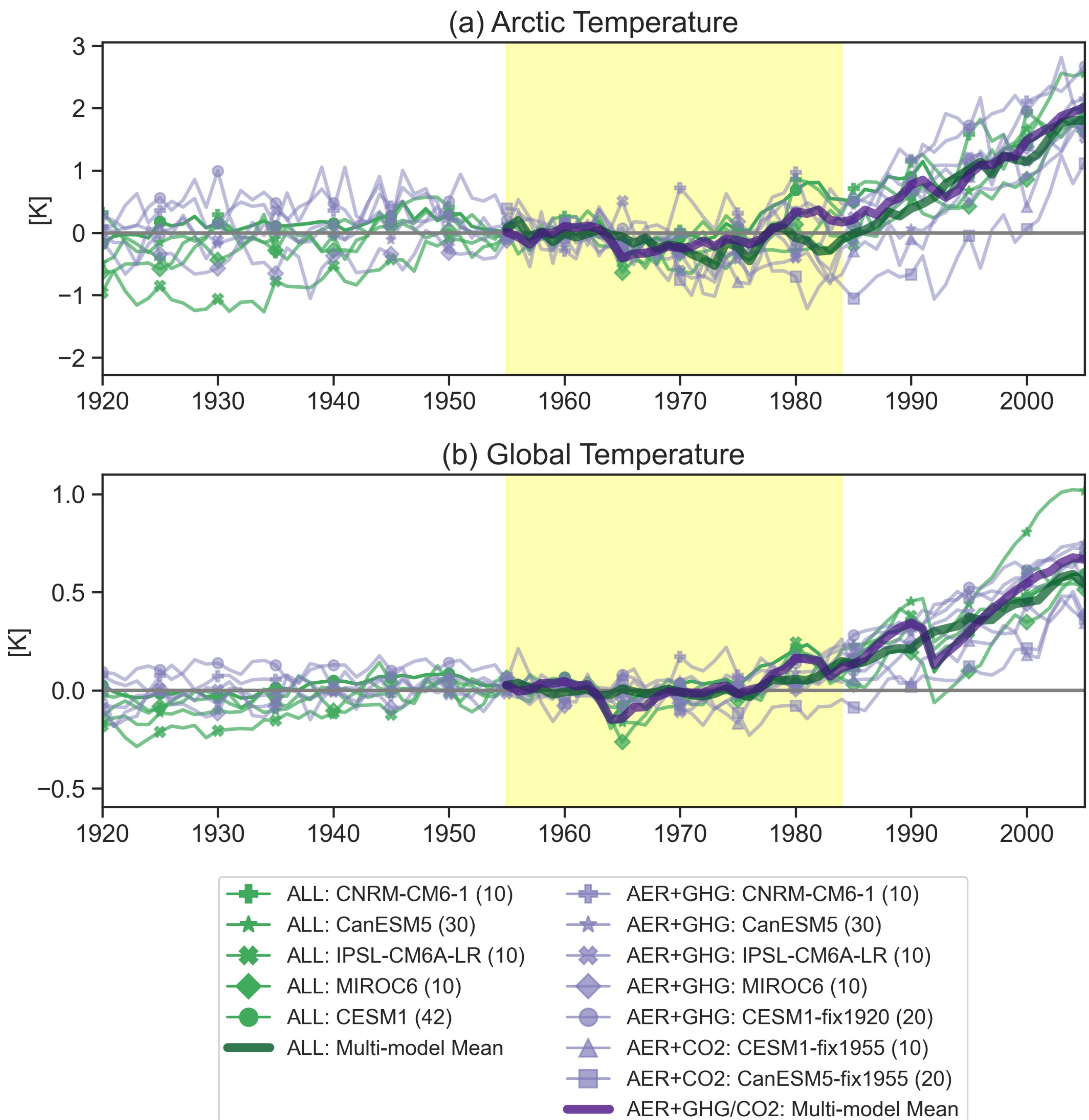
4. Pendergrass, A. G., Conley, A. & Vitt, F. M. Surface and top-of-atmosphere radiative feedback kernels for cesm-cam5. *Earth Syst. Sci. Data* **10**, 317–324 (2018).

Model Name	AER	GHG
CESM1-fix1920	3.760 [2.807, 4.768]	2.970 [2.494, 3.414]
CESM1-fix1955	3.865 [2.030, 5.581]	1.403 [-2.073, 3.846]
CanESM5-fix1955	4.350 [3.617, 4.980]	2.820 [1.354, 3.985]
CNRM-CM6-1	3.209 [0.689, 5.027]	2.947 [1.408, 5.903]
CanESM5	4.337 [3.978, 13.486]	2.635 [2.390, 6.479]
IPSL-CM6A-LR	4.378 [1.877, 7.193]	2.321 [-0.006, 4.482]
MIROC6	3.171 [1.032, 4.669]	2.299 [0.611, 3.728]
Multi-model	3.867 [3.394, 4.439]	2.485 [1.972, 2.990]

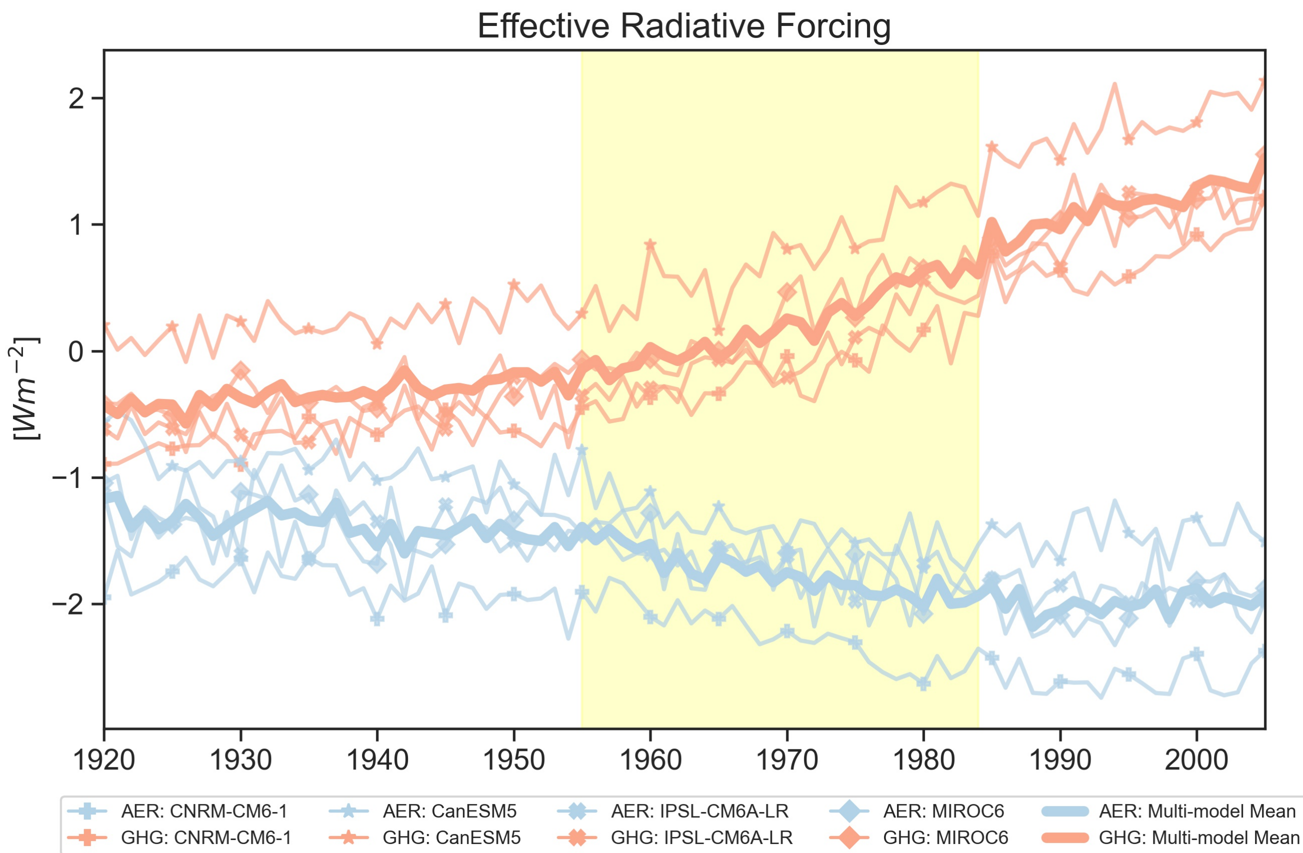
Supplementary Table 1. The mean and 95% confidence intervals of AAF across ensemble members for each climate model, as well as across the ensemble means of all models.



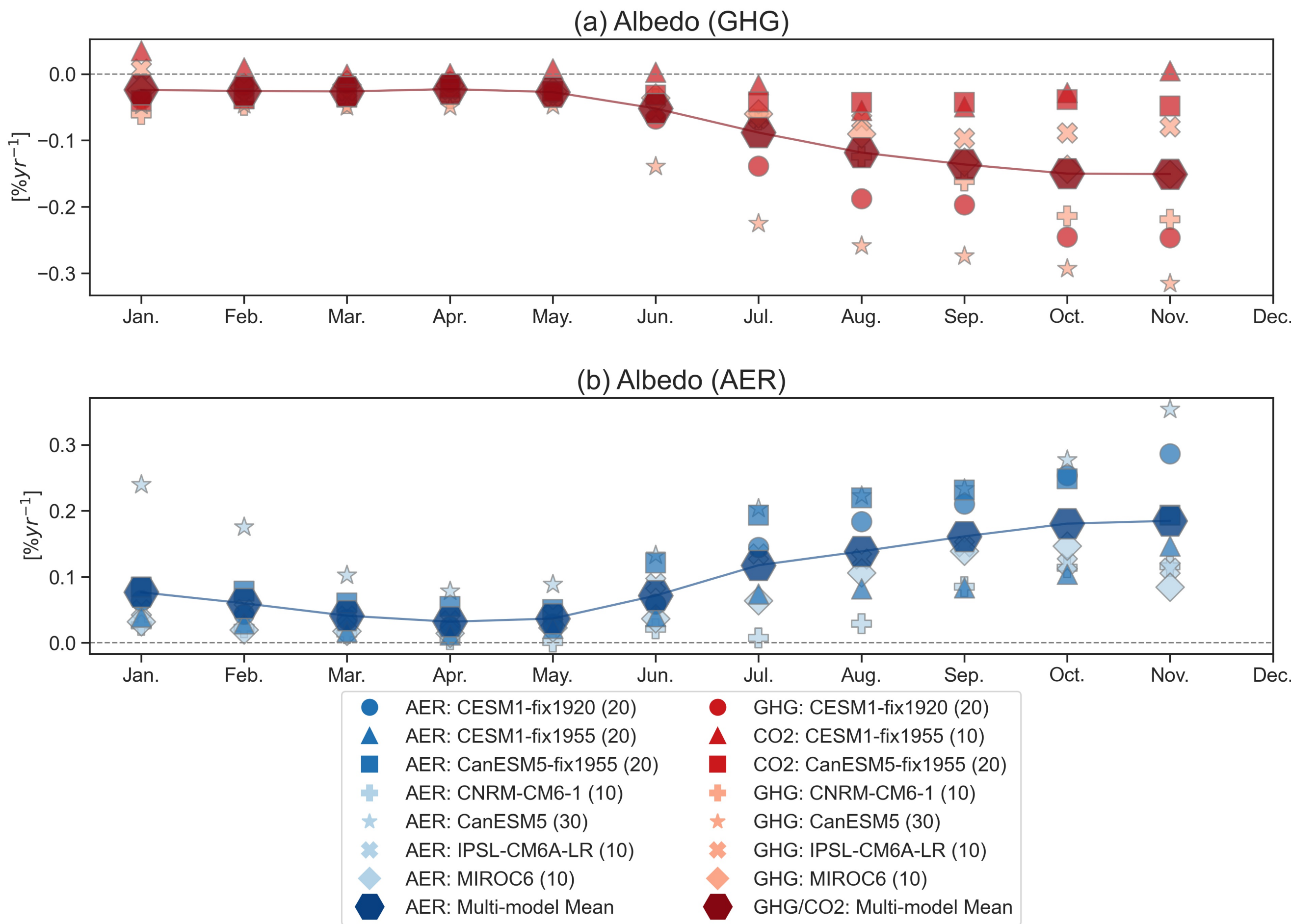
Supplementary Figure 1. The temporal evolutions of major GHG and AER emissions for both CMIP5 and CMIP6, from 1910 to 2010. a, CO_2 emissions. **b,** CH_4 emissions. **c,** N_2O emissions. **d,** Black carbon emissions. **e,** SO_4 emissions. **f,** SO_2 emissions. The yellow shading highlights the 1955-1984 period.



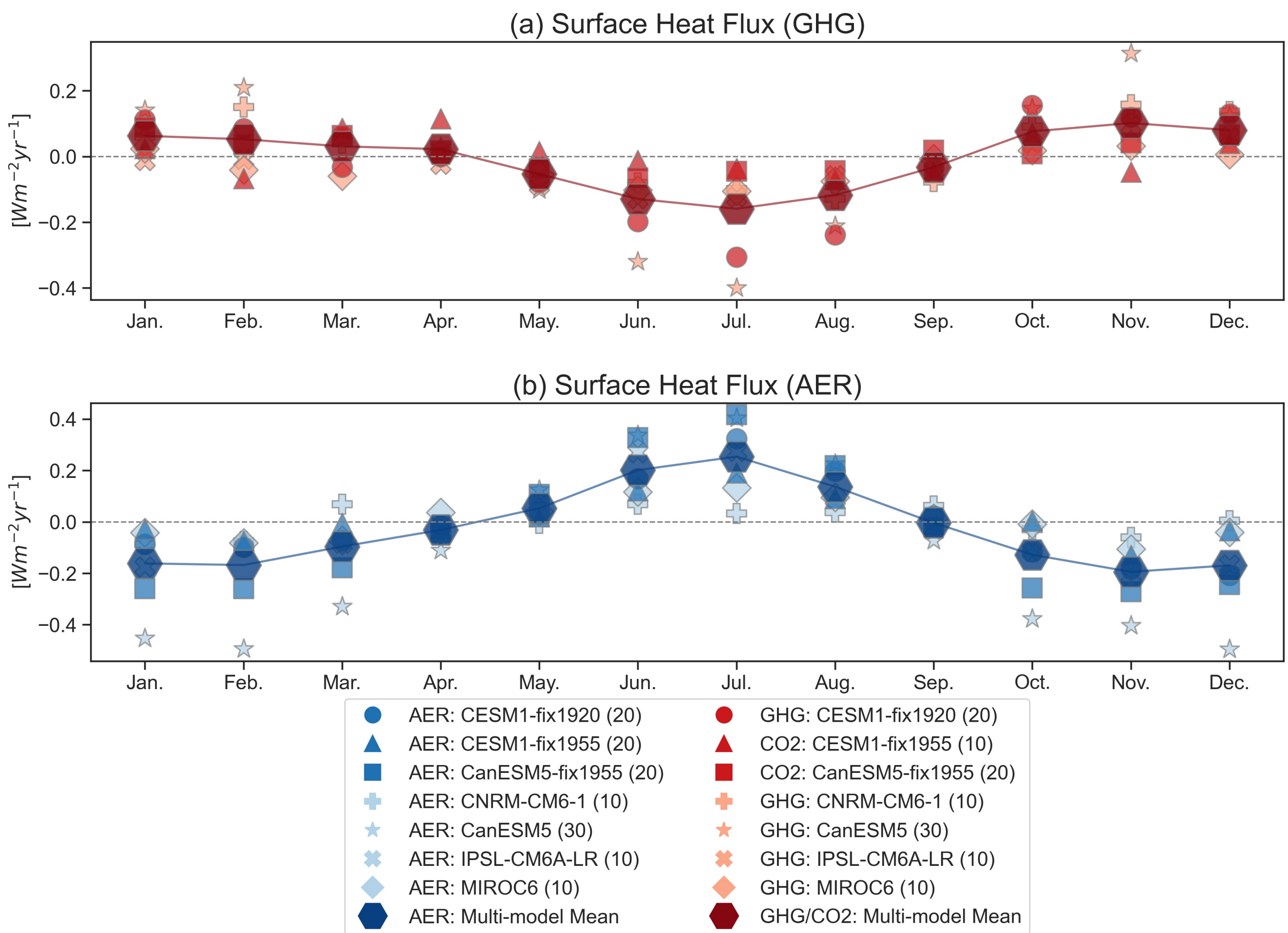
Supplementary Figure 2. The temporal evolutions of Arctic and global temperatures forced by all forcing agents and AER and GHG forcings combined, from 1920 to 2005. a, The ensemble-mean annual Arctic temperature changes forced by all forcing agents (green lines), and the sum of those forced by AER and GHG forcings (i.e., AER+GHG, purple lines). The reference values are to the corresponding 1955-1964 means. The thick lines represent the multi-model means. **b,** Same as **a**, but for the ensemble-mean global temperature changes. The number of ensemble members in each model is indicated in the parentheses of the figure legend, and the yellow shading highlights the 1955-1984 period.



Supplementary Figure 3. Global effective radiative forcing (ERF) for GHG and AER. The figure displays the annual mean ERF under AER (blue lines) and GHG (orange lines) for each model, referencing to the values from long-term mean in the corresponding pre-industrial simulations. The yellow shading highlights the 1955-1984 period.



Supplementary Figure 4. Seasonality of Arctic albdeo trends under GHG and AER forcings. a, Monthly ensemble-mean averages of the albedo trends for each model under GHG forcing. The bigger markers are the multi-model mean values. **b,** Similar to **a**, but under AER forcing. The number of ensemble members in each model is indicated in the parentheses of the figure legend.



Supplementary Figure 5. Seasonality of Arctic surface heat flux trends under GHG and AER forcings. The same as Figure S4, but for the seasonality of Arctic surface heat flux (SHF) trends.