Supporting Information for

Underestimated Future Arctic Ocean Warming due to Unresolved Marine Heatwaves at Low Resolution

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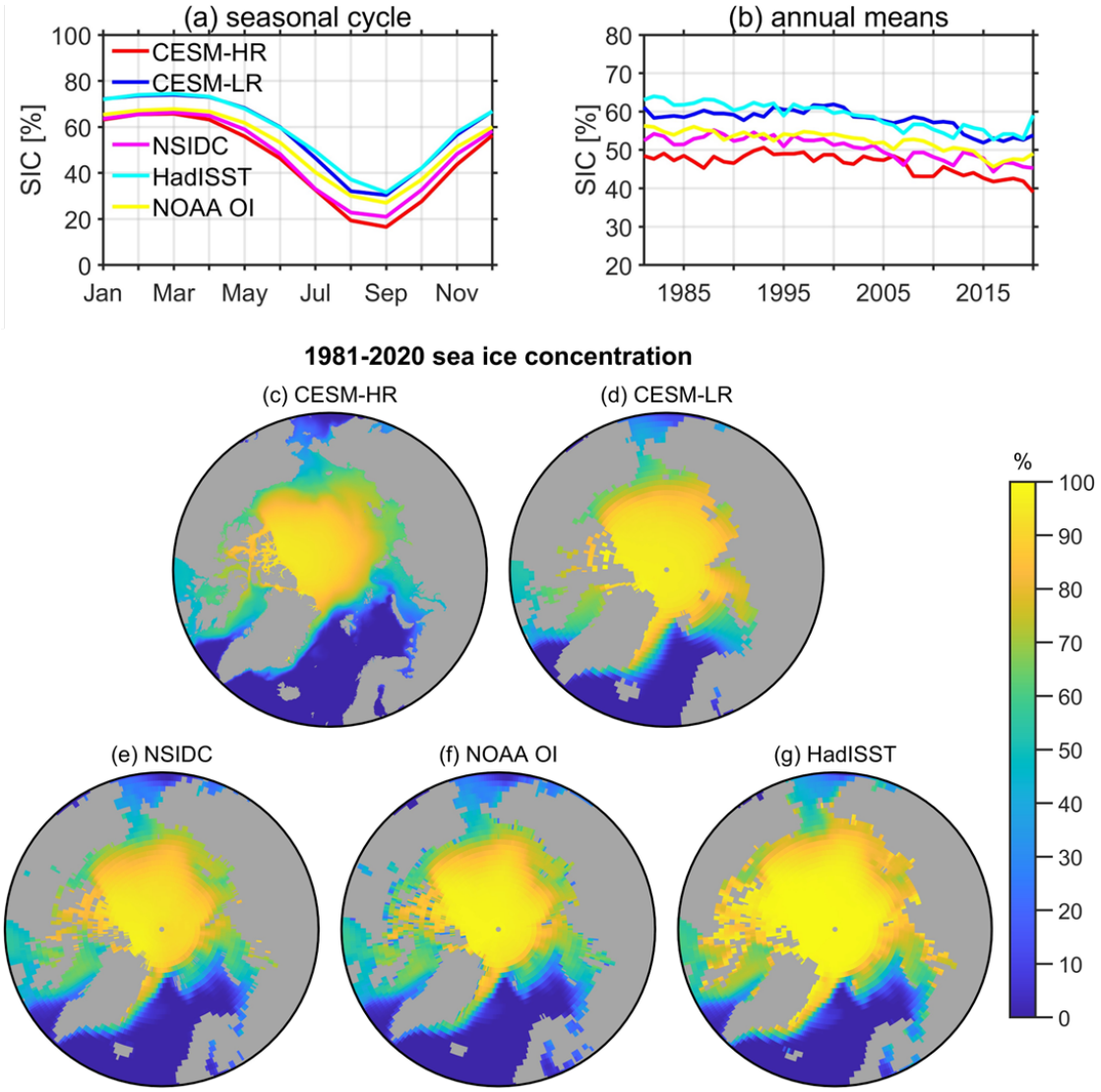

Fig. S1. Sea ice concentration in CESM-HR and CESM-LR and the comparison to observations. a-b, seasonal cycles (a) and annual means (b) of Arctic-mean (60-90°N) SIC in CESM-HR, CESM-LR and the observational datasets. d-h, the spatial distributions of time-mean SIC in 1981-2020.

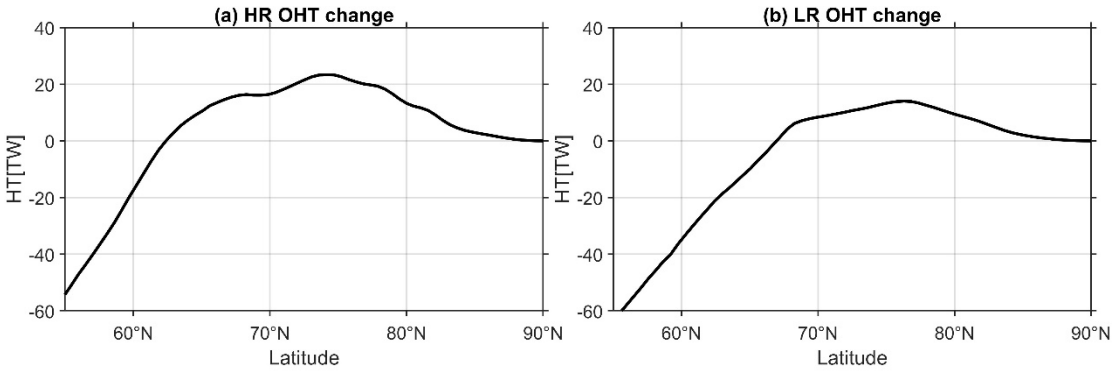

Fig. S2. Anomalous ocean heat transport in CESM-HR (a) and CESM-LR (b). "Anomalous" denotes the second-half mean minus the first-half mean of the periods.

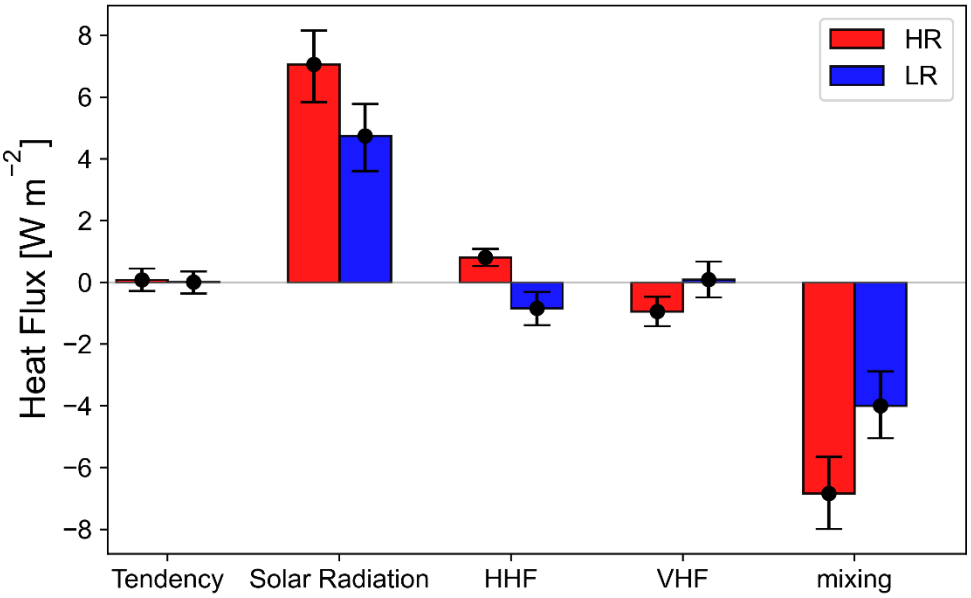

Fig. S3. Anomalous annual area-mean ocean heat budget in CESM-HR and CESM-LR. "Anomalous" denotes the second-half mean minus the first-half mean of the periods. The area averaging is performed for the north of 70°N (upper 50m), where most Arctic sea ice is located. HHF and VHF denote horizontal heat flux and vertical heat flux, respectively. The error bars represent 95% confidence intervals.

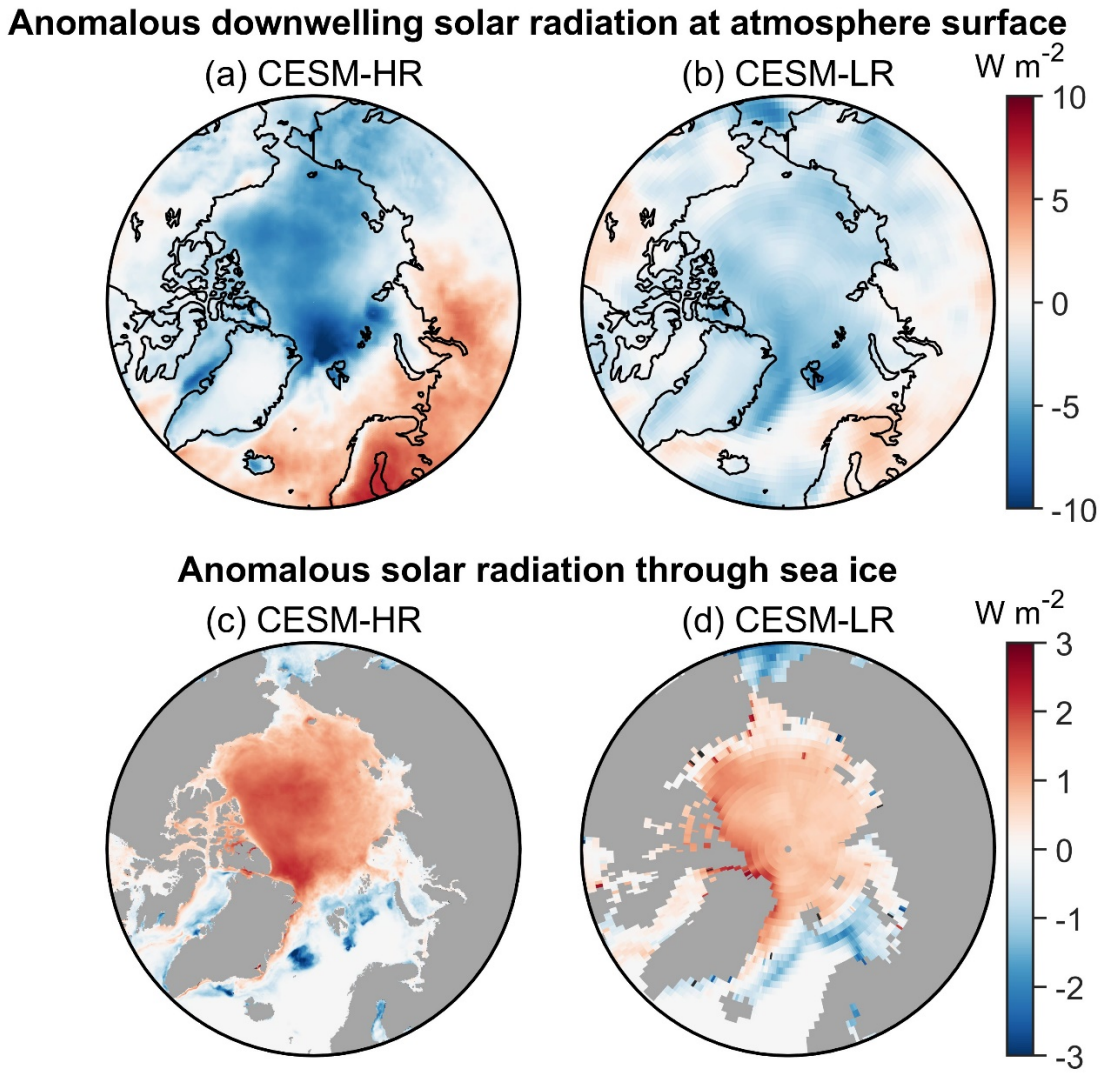

Fig. S4. Anomalous solar radiation at atmosphere surface and through sea ice in CESM-HR and CESM-LR. "Anomalous" denotes the second-half mean minus the first-half mean of the periods. a-b, spatial distributions of the anomalous downwelling solar radiation at atmosphere surface in CESM-HR (a) and CESM-LR (b). c-d, spatial distributions of the anomalous solar radiation through sea ice in CESM-HR (c) and CESM-LR (d).

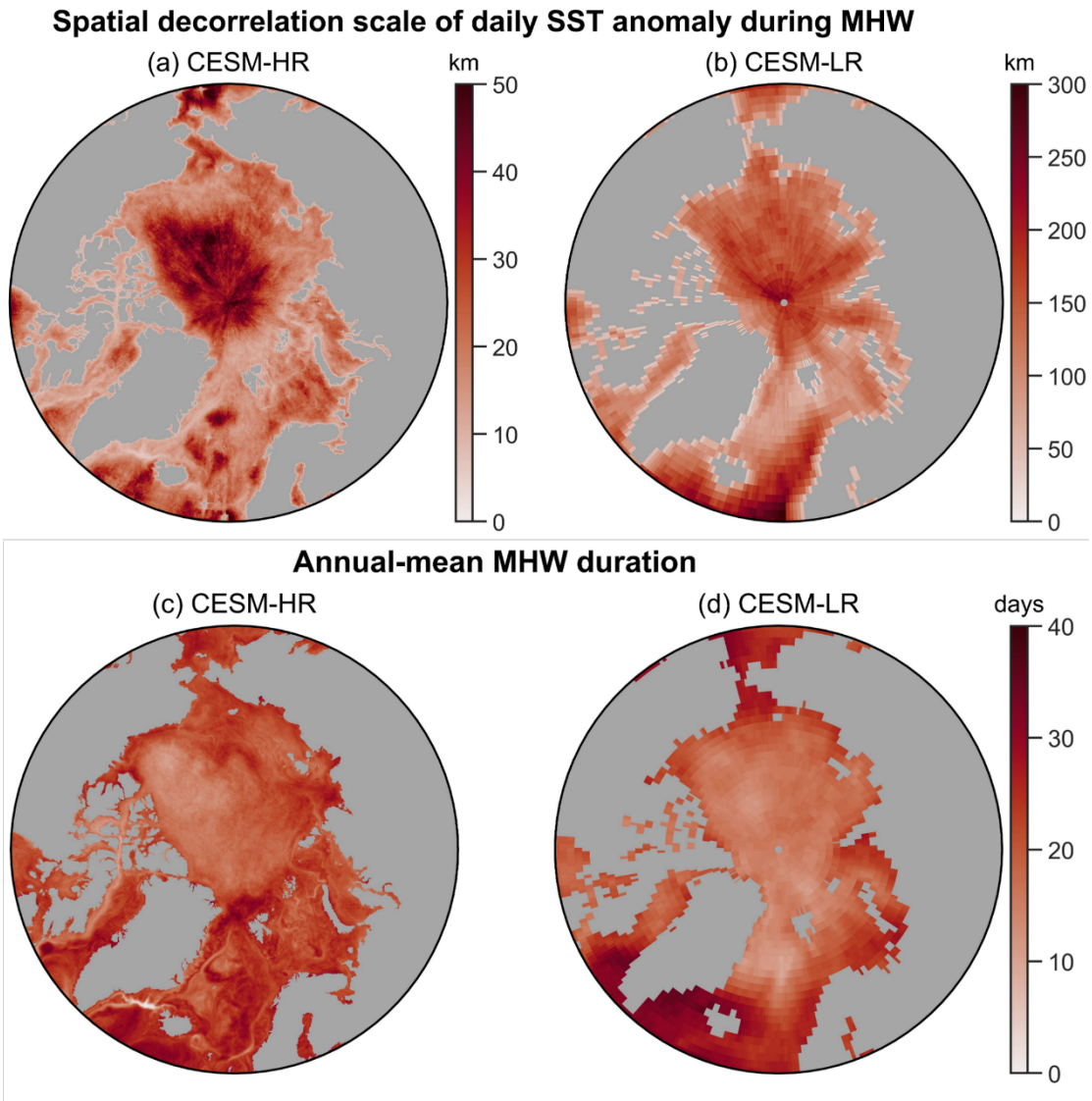

Fig. S5. Spatial scales and duration of marine heatwaves in CESM-HR and CESM-LR. a-b, time-mean spatial decorrelation scale of daily SST anomaly during MHW in CESM-HR (a) and CESM-LR (b). c-d, annual-mean MHW duration in CESM-HR (c) and CESM-LR (d).

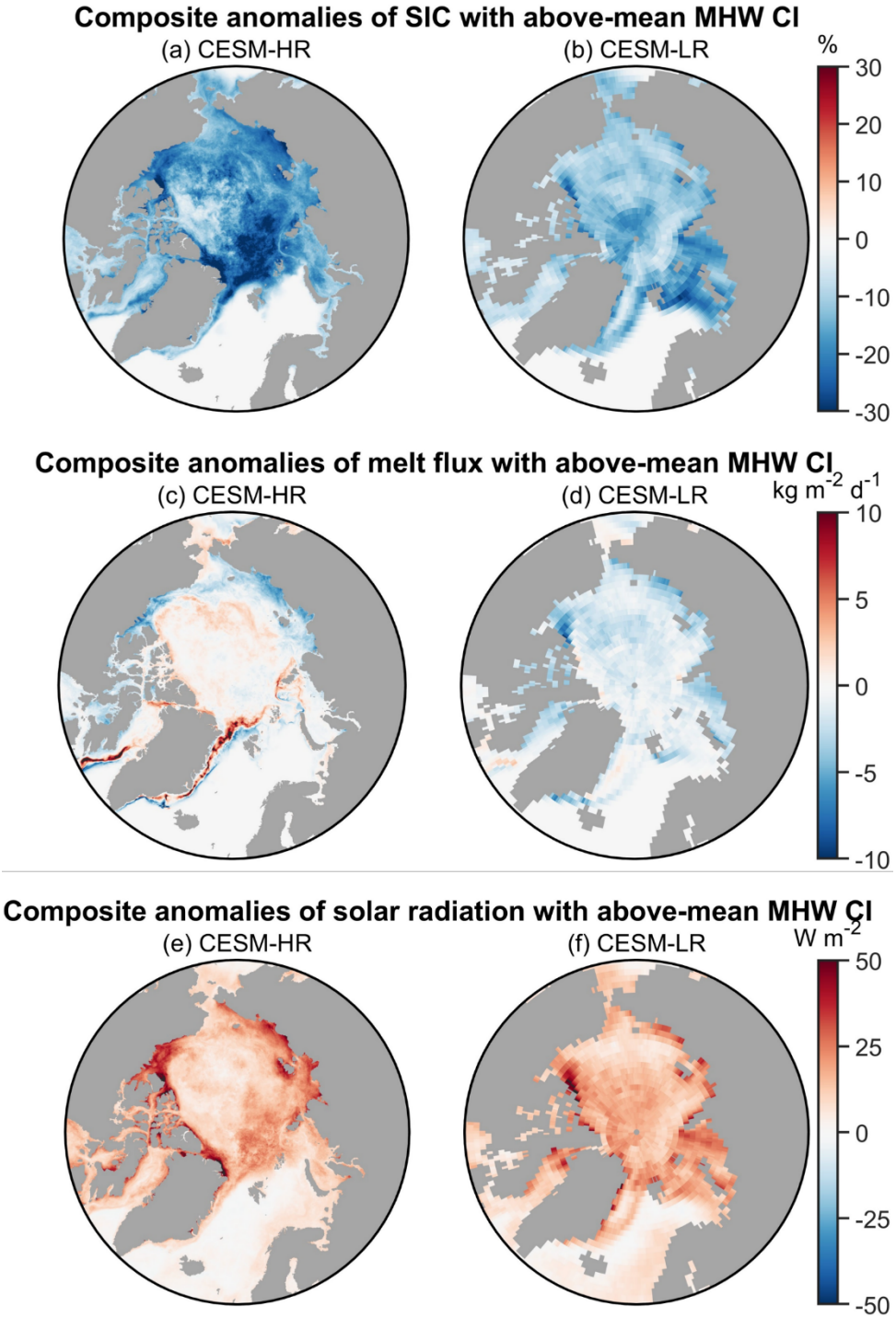

Fig. S6. Composite monthly anomalies with the cumulative intensity of marine heatwaves above average in CESM-HR and CESM-LR. a-b, the monthly composite anomalies of SIC in CESM-HR (a) and CESM-LR (b). c-d, the same as (a-b) but for melt flux. e-f, the same as (a-b) but for incoming solar radiation. Long-term trends and seasonal cycles are removed for SIC, melt flux and incoming solar radiation. The anomaly is relative to the period mean.

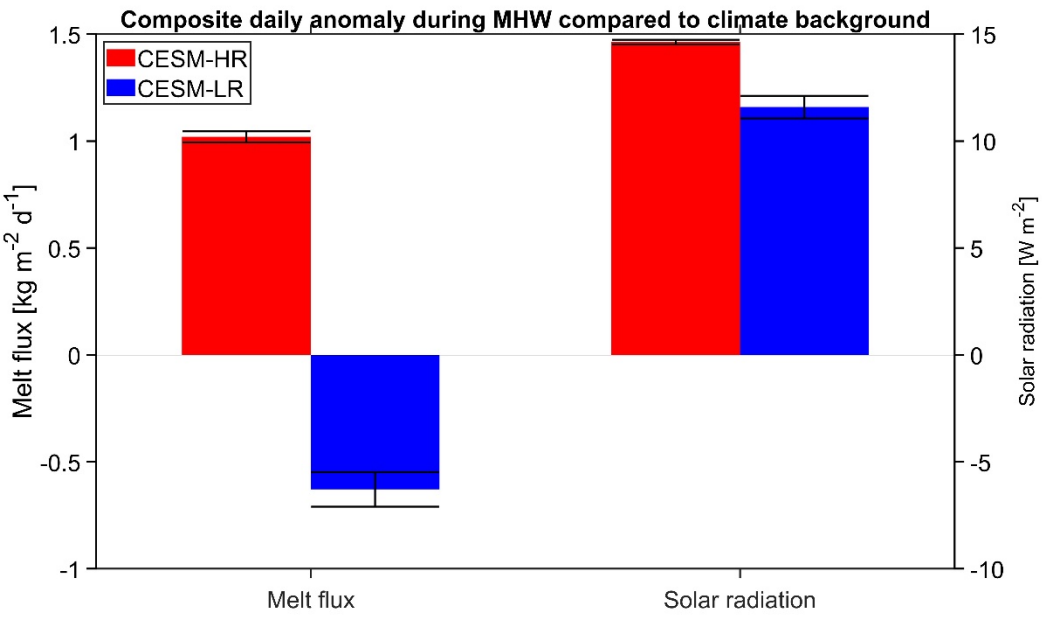

Fig. S7. Composite daily anomaly of melt flux and incoming solar radiation during marine heatwaves. The composite applies to all Arctic MHW days where some sea ice coverage is present. The anomaly is relative to the means of 31-year moving baseline periods. The error bars represent 95% confidence intervals.

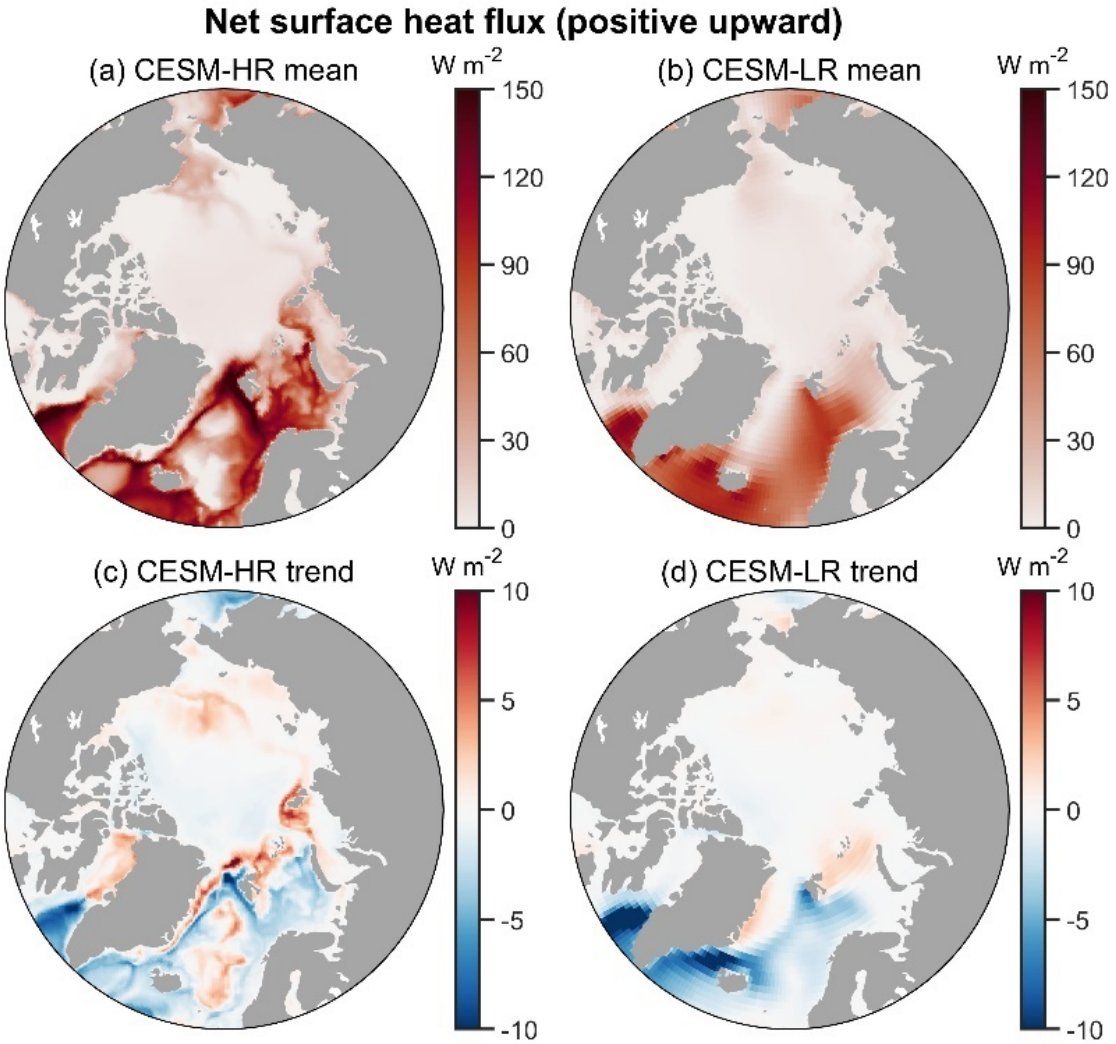

Fig. S8. Net surface heat flux in CESM-HR and CESM-LR. a-b, annual mean of surface heat flux in CESM-HR (a) and CESM-LR (b). c-d, linear decadal trend of surface heat flux in CESM-HR (c) and CESM-LR (d). Area-mean values of upward surface heat flux and its positive trend are 22.6 W m^{-2}, 0.59 W m^{-2} $decade^{-1}$ in CESM-HR and 15.9 W m^{-2}, 0.46 W m^{-2} $decade^{-1}$ in CESM-LR. The trends at where the magnitude is above 2 W m^{-2} $decade^{-1}$ are statistically significant at 95% confidence level.

High-resolution model versions from HighResMIP	Low-resolution model versions from HighResMIP
CESM1-CAM5-SE-HR (ocn-ice: 25km, atm: 25km)	CESM1-CAM5-SE-LR (ocn-ice: 100km, atm: 100km)
FGOALS-f3-H (ocn-ice: 10km, atm: 25km)	FGOALS-f3-L (ocn-ice: 100km, atm: 100km)
CMCC-CM2-VHR4 (ocn-ice: 25km, atm: 50km)	CMCC-CM2-SR5 (ocn-ice: 100km, atm: 100km)
CNRM-CM6-1-HR (ocn-ice: 25km, atm: 50km)	CNRM-CM6-1 (ocn-ice: 100km, atm: 250km)
EC-Earth3P-HR (ocn-ice: 25km, atm: 25km)	EC-Earth3P (ocn-ice: 100km, atm: 100km)
HadGEM3-GC31-HH (ocn-ice: 10km, atm: 50km)	HadGEM3-GC31-LL (ocn-ice: 100km, atm: 250km)

Table S1. HighResMIP models. The brackets indicate the nominal horizontal resolutions of the ocean (abbreviated as ocn), ice, atmosphere (abbreviated as atm) modules of the models.