The role of falling ice radiative effects on climate projections over Arctic under global warming

Jui-Lin Frank Li, Wei-Liang Lee, Kuan-Man Xu, Jonathan Jiang, Eric Fetzer, Chao-An Chen, Yi-Hui Wang, Jia-Yuh Yu, Pei-Chun Hsu, and Huang-Hsiung Hsu

SUPPLEMENTARY INFORMATION

Li et al. (2019) reported that recent Arctic sea ice retreat has been quicker than in most general circulation model (GCM) simulations. The figures here are used for citing in the main text. More details please refer to Li et al. (2019).

Shown in Fig. S1 is for the March and September post-1979 changes in SIE in NSIDC observations and CMIP5 simulations. The upper right panel shows that observed September retreat approaches the lower 10^{th} percentile of the CMIP5 ensemble. The bottom panels of this figure show that the CMIP5-SoN sub-ensemble generally agrees better with the faster observed retreat. In March, trends are similar but CMIP5-SoN shows greater extent, which is the opposite of expectations if wintertime longwave from FIREs were the main cause of differences. However, differences in parameterisations for clouds, the atmosphere, oceans and sea ice can change the mean state, so we isolate FIREs by using controlled CESM1 simulations by turning on and off FIREs.

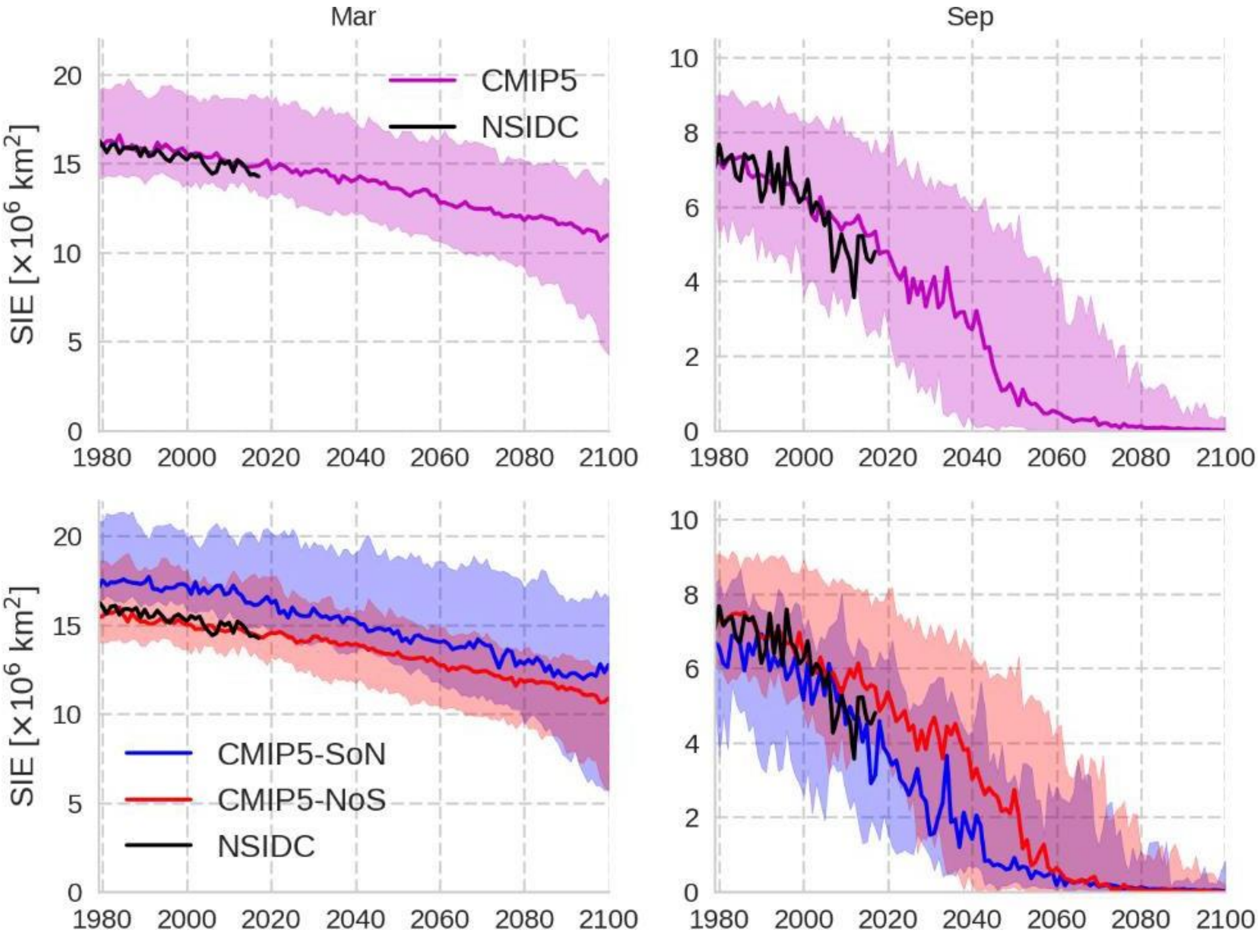

Fig. S1. Arctic sea ice extent during March (left) and September (right) in NSIDC observations (black) and CMIP5 climate models (line median, shaded 10 - 90% range). The upper row shows the full CMIP5 ensemble. The bottom row shows the ensemble split into those including snow radiative effects (blue) and those excluding snow radiative effects (red).

The role of falling ice radiative effects on climate projections over Arctic under global warming

Jui-Lin Frank Li, Wei-Liang Lee, Kuan-Man Xu, Jonathan Jiang, Eric Fetzer, Chao-An Chen, Yi-Hui Wang, Jia-Yuh Yu, Pei-Chun Hsu, and Huang-Hsiung Hsu

We found that CESM1-CAM5 captures the mean extent well with a smaller discrepancy versus observations throughout the year when including FIREs (Li et al. 2019). Historical retreat is also faster in CESM1-SoN than in CESM1-NoS, but it is only significant if white noise is assumed (t = 2.39, p = 0.012), whereas after accounting for lag-1 autocorrelation above 0.4 the difference is insignificant (t = 1.51, p = 0.073). Neither show significant differences relative to NSIDC observations over 1979 - 2005 although the 1979 - 2017 trend is detectably faster than the CESM1-NoS changes through 2005. The bottom panels show that inclusion of FIREs results in a much faster September retreat beginning around year 40 of the simulation in the 1pctCO_2 simulation.

Shown in Fig. S2 is for local radiative feedbacks differences when including or excluding FIREs, for SoN minus NoS flux differences in time. The figure includes $SW_{\downarrow}$ and $LW_{\downarrow}$ differences for each season: December-January-February (DJF), March-April-May (MAM), June-July-August (JJA), and September-October-November (SON). Long-term changes are estimated by multiplying the trend gradient by the length of the period, and the only significant ($p < 0.05$) changes occur in SON, where there is a decrease in the radiative flux difference between the two simulations.

However, the SoN minus NoS LW↓ trend is insignificantly positive during the first 70 years (+0.08 ± 0.09 W m^{-2} yr^{-1}), so this change is not responsible for driving the faster disappearance of sea ice in CESM1-SoN which has largely occurred by year 70. Instead, the difference appears related to differences in the relative effects of FIREs between icy and ice-free states. During the first 40 years when the simulations both have a healthy Arctic ice cover the median SON difference in $LW_{\downarrow}$ is 11.2 W m^{-2} (6.4 - 16.9 W m^{-2}, henceforth bracketed values are 14 - 86% range) whereas for the final 40 years where both simulations are ice free during September, the difference is 6.8 (4.9 - 10.2) W m^{-2}. Some combination of cloud properties or precipitation phase, such as the transition from snow to rain under warming, likely explain this difference.

The energy budget analysis of CESM1-CAM5 1pctCO_2 simulations indicates that differences in flux trends due to FIREs do not drive the faster observed retreat, but instead the effect of stronger year-round $LW_{\downarrow}$ in the initial state is the most important radiative contribution. This supports our argument that the effective greenhouse effect from snowflakes results in a thinner pack whose retreat is more easily triggered by warming. This impact of FIREs is present year round and throughout the entire Arctic basin, leaving no safe spaces where the ice can fully recover.

REFERENCES

Li, J.-L. F., M. Richardson, W.-L. Lee, E. Fetzer, G. Stephens, J. Jiang, Y. Hong, Y.-H. Wang, J.-Y. Yu, and Y. Liu, 2019: Potential faster Arctic sea ice retreat triggered by snowflakes' greenhouse effect. *The Cryosphere*, **13**, 969-980, doi: 10.5194/tc-13-969-2019. [Link]

The role of falling ice radiative effects on climate projections over Arctic under global warming

Jui-Lin Frank Li, Wei-Liang Lee, Kuan-Man Xu, Jonathan Jiang, Eric Fetzer, Chao-An Chen, Yi-Hui Wang, Jia-Yuh Yu, Pei-Chun Hsu, and Huang-Hsiung Hsu

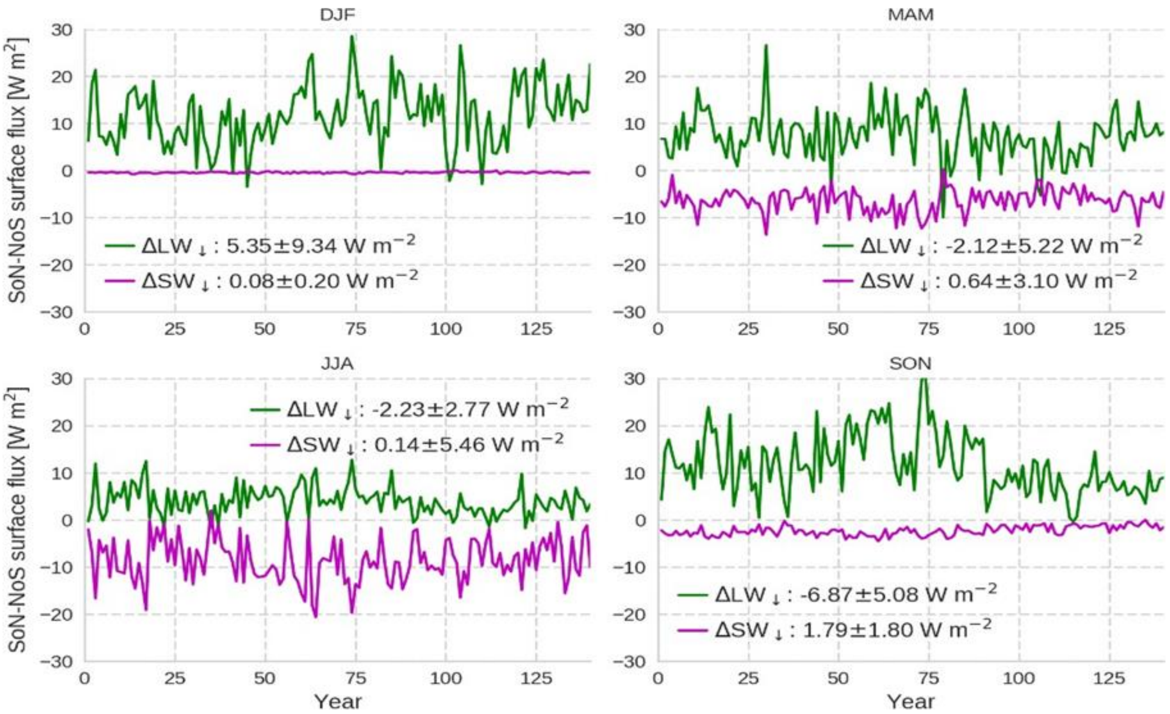

Fig. S2. CESM1-SoN minus CESM1-NoS season differences in downward surface fluxes over 60 - 90°N oceans. The legend reports the estimate of the 140-year change in this difference by multiplying the linear regression trend coefficient by 140, with ±2σ uncertainties.