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Influences of changing sea ice and snow thicknesses on simulated Arctic winter heat fluxes

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Supplemental Material

CESM1-LE vs 0-layer model

We explore the influence of sub-grid scale heterogeneity in sea ice and snow fields on conductive heat fluxes by using the Semnter 0-layer model to calculate conductive heat fluxes from daily grid-cell mean sea ice and snow thicknesses and surface temperatures, and then compute monthly averages to compare with the conductive heat fluxes from the model. Sea ice thermodynamics in the CESM1-LE are calculated for each of the five discrete ice thickness categories using the multi-layer thermodynamic scheme of Bitz and Lipscomb (1999) which includes the effects of a prescribed vertical salinity profile and time-evolving vertical temperature profile – a more complete and yet more complex calculation than the Semtner 0-layer model. Differences between the conductive heat fluxes calculated from the grid-cell mean variables and the model output will be due to differences in the thermodynamic models (Semtner and CESM1-LE) as well as differences due to thickness distributions.

We assess how well the 0-layer model of Semtner estimates conductive heat fluxes compared to CESM1-LE by evaluating daily output from three 30-member CESM1 ensembles that were run for 2-year time slices (1980-1981; 2021-2022; and 2051-2052) using the same forcing as the CESM1-LE (hereafter referred to as the CESM1-TS; DuVivier et al., 2020). These experiments – unlike the CESM1-LE – included daily output of ice and snow thicknesses in each of the five discrete thickness categories, enabling us to compare conductive heat fluxes calculated using the ice thickness distribution (ITD) and the 0-layer model to the climate model output. Daily grid-cell mean surface temperatures were used as neither the CESM1-LE nor the CESM1-TS output sub-gridcell surface temperature information. Furthermore, the CESM1-LE output daily surface temperatures on the atmosphere grid but not on the sea-ice grid, so surface temperatures from the daily atmosphere model were regridded onto the ice grid for all conductive heat flux calculations. Comparisons between these calculations using regridded atmospheric surface temperatures and those from the CICE model component were compared in CESM1-TS (which output both) confirmed that using re-gridded atmospheric output did not substantially change the results.

Mean Arctic ocean differences between model output (CESM1-LE) conductive heat fluxes and those calculated using grid-cell mean values of ice and snow thicknesses (MNthick) tend to be an order of magnitude larger than those calculated using heterogeneous ice and snow fields ("0layer-ITD"; Supplemental Fig. 1) for most winter months. In the months of January and February for each of the time slices, 0layer-ITD estimates lie within 0.6 W/m^2 (or 2.1%) from the CESM1-LE calculations (Supplemental Table 1), whereas those using the grid-cell means are less than the model outputs by 5.6-9.5 0.6 W/m^2 (or 15.5-

39.1%). Conductive heat fluxes increase in all calculations as sea ice thins, despite decreases in temperature gradients, and the errors from the model output increase/decrease for the 0-layer estimates using ITD/grid-cell mean sea ice and snow thicknesses.

References

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Supplemental Table 1. Ensemble mean differences between CESM1 monthly conductive heat fluxes (CESM1-LE) and those calculated using the Semtner 0-layer model with sea ice and snow thicknesses from the 5 thickness categories (0layer-IDT) and from grid-cell mean sea ice and snow thicknesses (MNthick) for three time-slices.

method	CESM1-LE - (0layer-IDT)						CESM1-LE – (MNthick)					
year	1980-1981		2021-2022		2051-2052		1980-1981		2021-2022		2051-2052	
month	W m^{-2}	%	W m^{-2}	%	W m^{-2}	%	W m^{-2}	%	W m^{-2}	%	W m^{-2}	%
10 (Oct)	-1.9	-8.3	0.7	3.4	0.6	11.4	-12.7	-54.3	-7.6	-40.1	-1.7	-31.6
11 (Nov)	-1.3	-4.4	1.3	4.0	3.7	17.6	-12.8	-43.4	-7.6	-22.8	0.6	2.9
12 (Dec)	-0.6	-2.3	-0.0	-0.1	2.3	6.1	-11.2	-40.8	-8.9	-25.3	-2.5	-6.7
13 (Jan)	-0.2	-0.7	0.3	1.0	0.5	1.3	-9.5	-39.1	-8.2	-27.1	-5.6	-15.5
14 (Feb)	0.4	1.9	0.5	1.8	0.6	2.1	-8.4	-38.1	-7.9	-29.2	-6.0	-20.0
15 (Mar)	0.9	5.1	1.	4.7	0.9	3.7	-6.9	-37.4	-6.5	-29.8	-5.8	-24.1

Figure captions

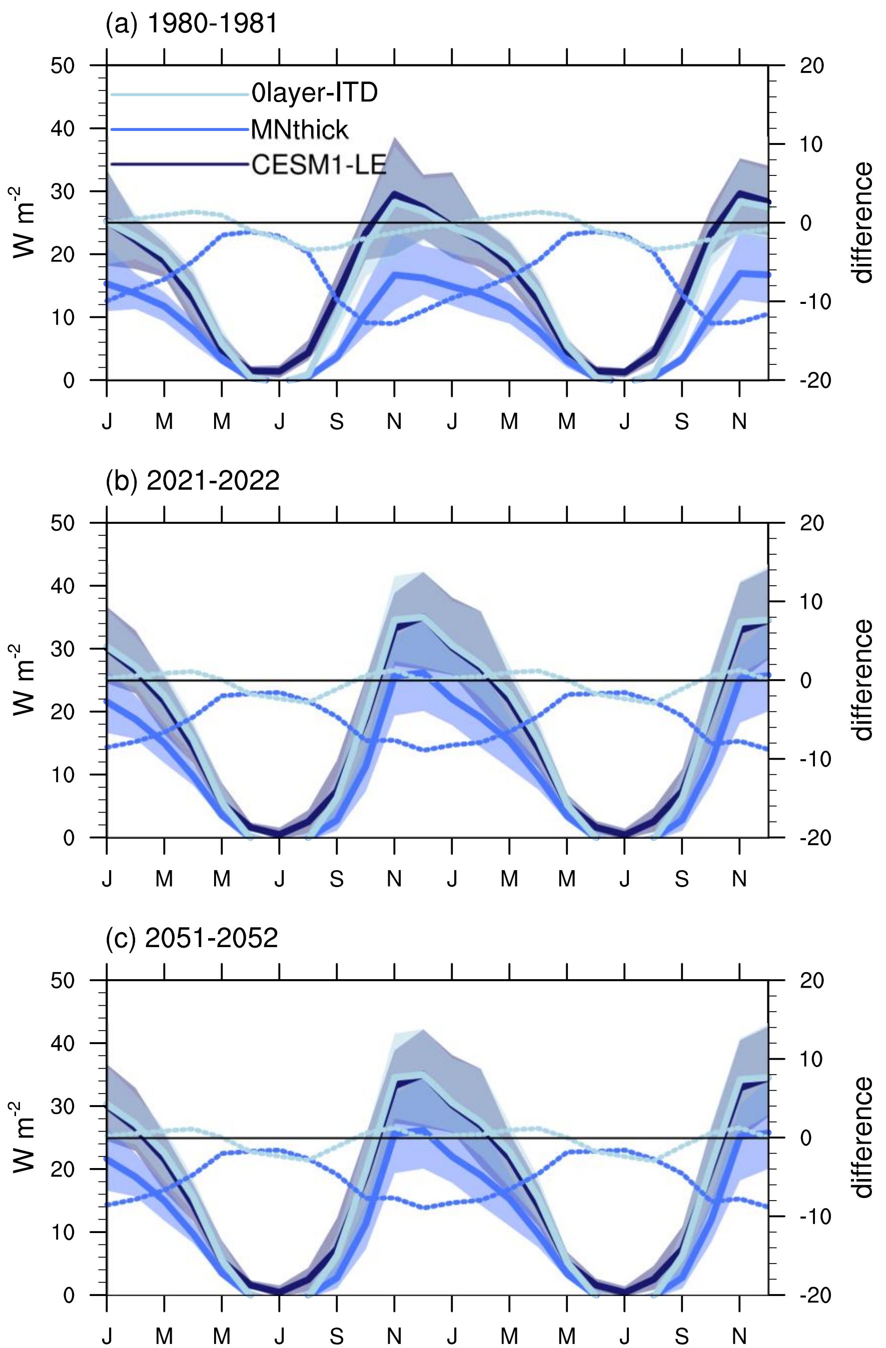
Supplemental Figure 1. CESM1 two-year timeseries of area-averaged Arctic Ocean conductive heat fluxes from the model output (CESM1-LE; navy blue) and the Semtner 0-layer model calculations using daily sea ice and snow thicknesses from 5 discrete thickness categories (0layer-ITD; light blue) and using grid-cell mean sea ice and snow thicknesses (MNthick; medium blue). Differences from the model output are shown in dotted lines with scale on the right for both 0-layer model calculations (0layer-ITD in light blue, MNthick in medium blue). Ensemble means are show in the solid lines, ensemble ranges in opaque polygons. Arctic Ocean region is shown in the map insert in the middle panel in Fig. 1.

Supplemental Figure 2. CESM1-LE February ensemble decadal mean (a-c) and decadal mean differences (d-i) in sea ice thickness (a, d, g), snow thicknesses (b, e, h) and effective snow thicknesses, $K_{ratio}*h_s$ (c, f, i). The 98% SIC for each decade is shown by the thick black contour. Stippled areas and dotted contour line indicate regions where mean/changes in effective snow thickness ($K_{ratio}*h_s$) account for 40% or more of the mean/changes in the total effective thickness (heff = SIT + $K_{ratio}*h_s$).

Supplemental Figure 3. Decadal mean differences between February conductive heat fluxes from the model output (CESM1-LE) and those calculated using grid-cell mean thicknesses (MNthick) for the 2010s (a) and 2050s (b).

Supplemental Figure 4. October decadal mean changes (from 1950-1959) in Arctic Amplification ($\Delta TAS/\Delta TAS_{global}$; a), net surface heat fluxes (b), sea ice contribution to surface heat fluxes (c), and ocean contributions to surface heat fluxes (d) for the 2010s. The 98% SIC for each decade is shown by the thick black contour.

Arctic Ocean conductive heat flux



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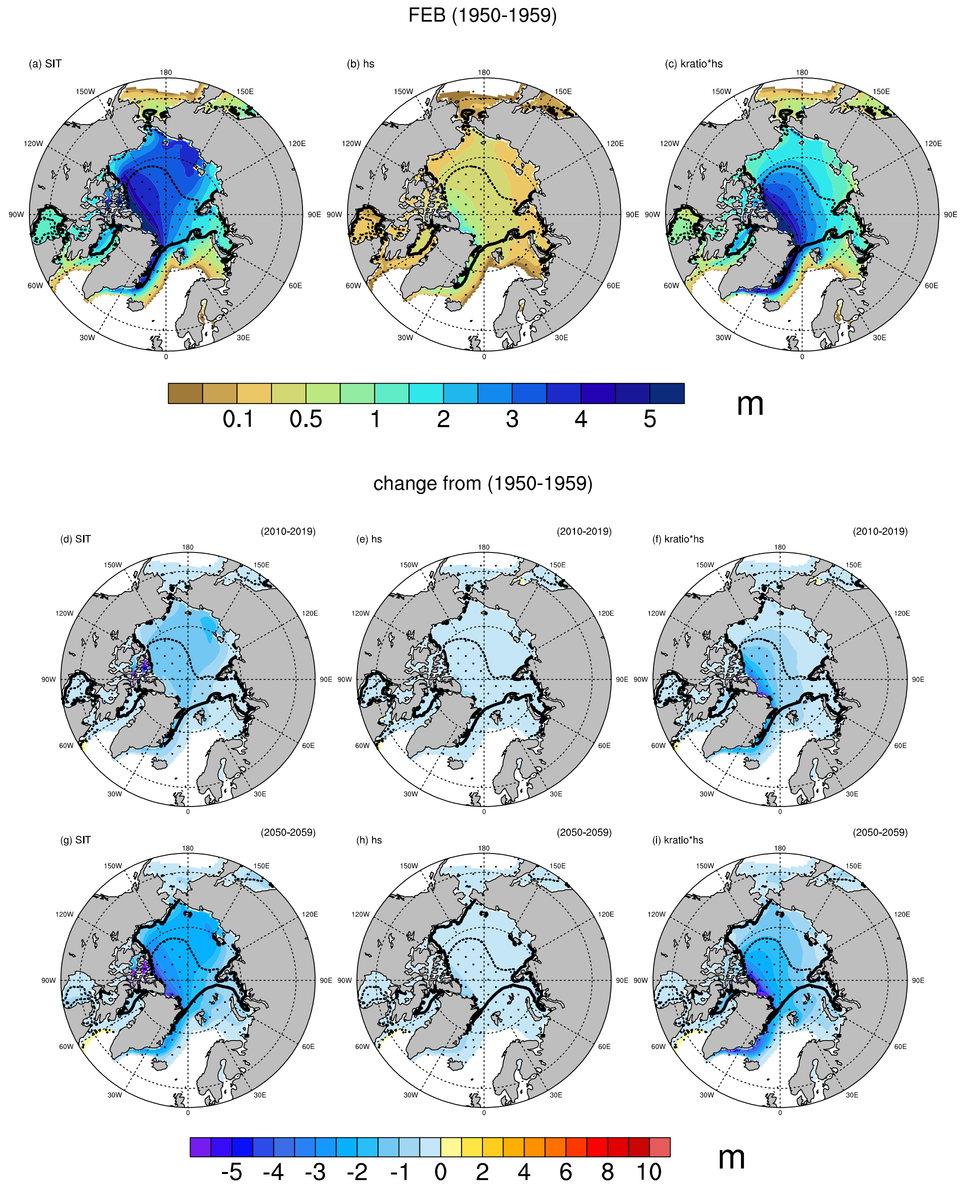
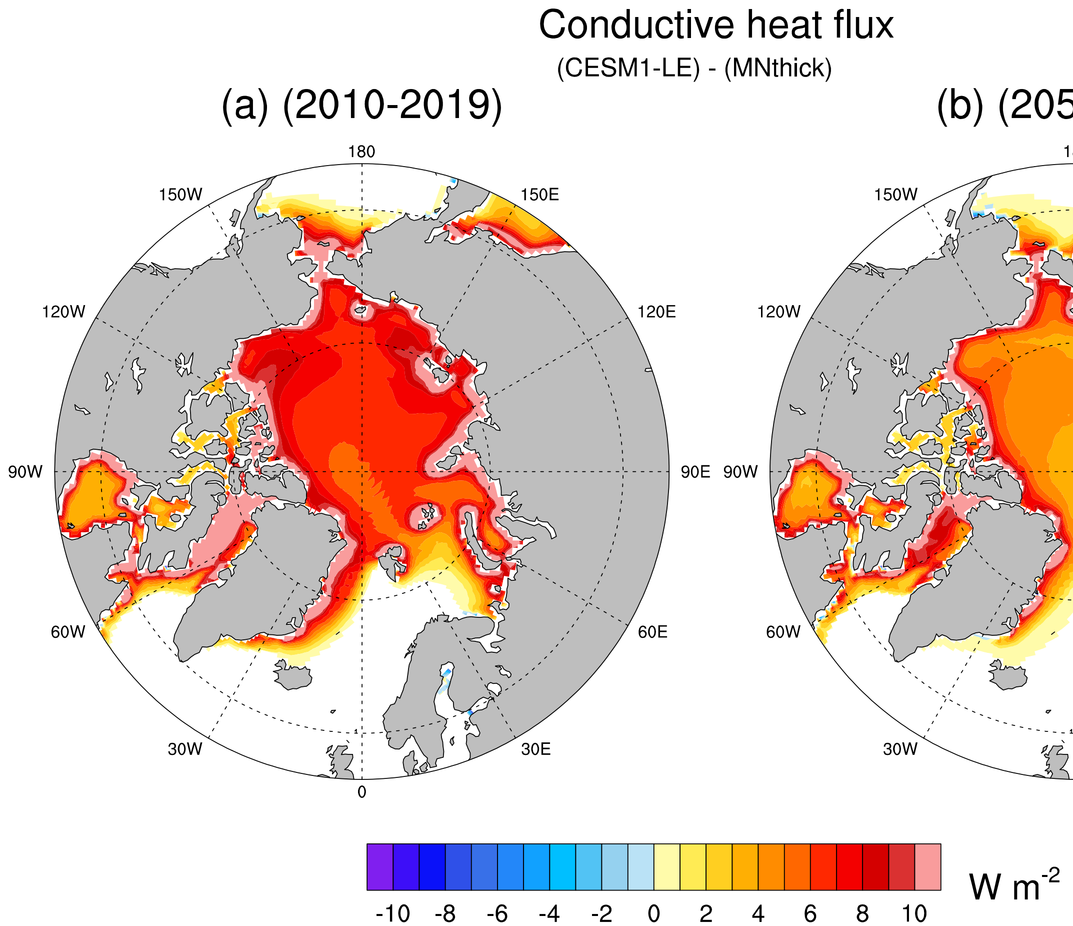
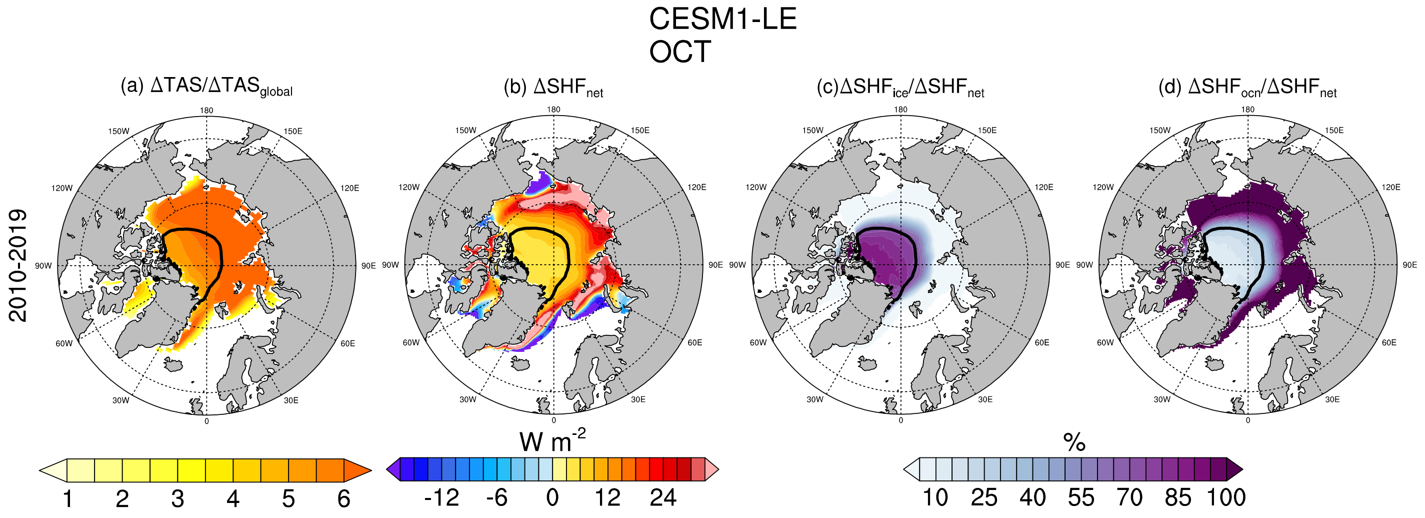
Supplemental Figure 1



Supplemental Figure 2



80 **Supplemental Figure 3**



Supplemental Figure 4