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Supporting Information for

Less surface sea ice melt in the CESM2 improves Arctic sea ice simulation with minimal non-polar climate impacts

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Introduction

The supporting information for this paper includes justification for the “equal likely” assumption (Text S1, Figures S1-S5) and figures that are useful for reference but not essential for the main text (Figures S6-S10).

Text S1. Equally likely assumption and initial condition memory

We make an "equally likely" assumption for all ensemble members analyzed in this work. In other words, we assume each ensemble member provides an equally likely estimate of transient climate evolution in the late 20th and 21st century with no memory of the initial condition. While atmospheric initial condition memory is limited to weeks, the timescale over which ocean initial conditions can influence climate is not well known. Indeed, memory associated with the ocean can persist on decadal and longer timescales (e.g., Yeager et al. 2015, Latif et al. 2013).

Unlike the CESM2-tunedice ensemble members, the CESM2-LE ensemble members used in this study do not all share the same ocean initial condition. Thus, ocean initial condition memory may invalidate our "equally likely" assumption for the CESM2-LE. As described in Rodgers et al. (2021), CESM2-LE initial conditions were selected to generate spread in the ocean initial conditions. Members 1-10 and 91-100 ("macro") were started every 10 years starting at year 1001 of the PI control and thus all have differing ocean initial conditions. In contrast, the rest of the members are split into mini ensembles of 20 members that share the same ocean initial conditions. The initial condition for each mini ensemble was selected to maximize differences in the Atlantic Meridional Overturning Circulation (AMOC) states: "micro1231" started at year 1231, "micro1251" started at year 1251, "micro1281" started at year 1281, and "micro1301" started at year 1301. Within each 20-member micro ensemble, the ensemble member initial conditions differ only in their atmospheric temperature at the round-off level. The first 50 members do not share late 20th century forcing with the last 50 members or with CESM2-tunedice. As a result, analysis in the main text only uses members 1-50 of CESM2-LE. That said, we use all CESM2-LE members here because their forcing is the same over the time period when initial condition memory is lost.

The four variables primarily analyzed in this work (global mean surface air temperature, Arctic mean surface air temperature, Arctic sea ice extent, and Arctic sea ice volume) differ in their ensemble spread and variability. Over the first month of the ensemble (January 1850), global and Arctic surface air temperatures rapidly diverge and visually retain little initial condition memory (**Figure S1**). In contrast, Arctic sea ice extent and volume remain visually similar for ensemble members with shared ocean initial conditions. Thus, Arctic sea ice volume and extent retain more memory of the ocean initial condition during the first month of the ensemble than surface air temperatures do. Consistent with previous work (Holland et al. 2011, Blanchard-Wrigglesworth et al. 2011), Arctic sea ice volume has more memory than Arctic sea ice extent. By January of year 15, Arctic sea ice differences related to ocean initial condition were harder to identify indicating substantial initial condition memory loss.

We next quantify initial condition memory loss for the four variables primarily analyzed in this work. To do so, we compare pre-industrial control statistics calculated over time to transient statistics calculated across ensemble member in each mini CESM2-LE ensemble. To generate the pre-industrial control statistics, we calculate 95% confidence intervals from a distribution of sample means and standard deviations found by bootstrapping 10,000 times with N=10 from the CESM2 pre-industrial control (years 1000-1200). In other words, we randomly select 10 daily values from the CESM2 pre-industrial control run 10,000 times generating a distribution from which 95% confidence intervals are calculated. We assume initial condition memory is lost when statistics calculated using the spread across ensemble members lies within the pre-industrial distribution. This method requires us to assume forced climate change is small in the first decades of the CESM2-LE, i.e., starting from 1850 onward. In addition to this first method, we also compare ensemble statistics from each micro to the ensemble statistics of macro using a t-test for the mean and an f-test for the variance. This second method requires us to assume that the variables are normally distributed and relies on comparing two relatively small (N=20) samples. As the results are similar for both methods, we only show results from the first method.

After 20 years, the CESM-LE has lost almost all initial condition memory for the four variables we examined: global surface air temperature, Arctic surface air temperature, Arctic sea ice extent, and Arctic sea ice volume. The longest initial condition memory comes from the micro1301 ensemble, which has sea ice volume and winter sea ice extent that are statistically larger than the pre-industrial control (**Figure S2, Figure S3**). Arctic surface air temperatures and global air temperatures offer little evidence for persistent initial condition memory (**Figure S4, Figure S5).**

In summary, the equally likely assumption is appropriate in the late 20th and early 21 centuries. Thus, we compare the CESM2-LE members with the CESM2-tunedice members without considering ocean initial condition memory.

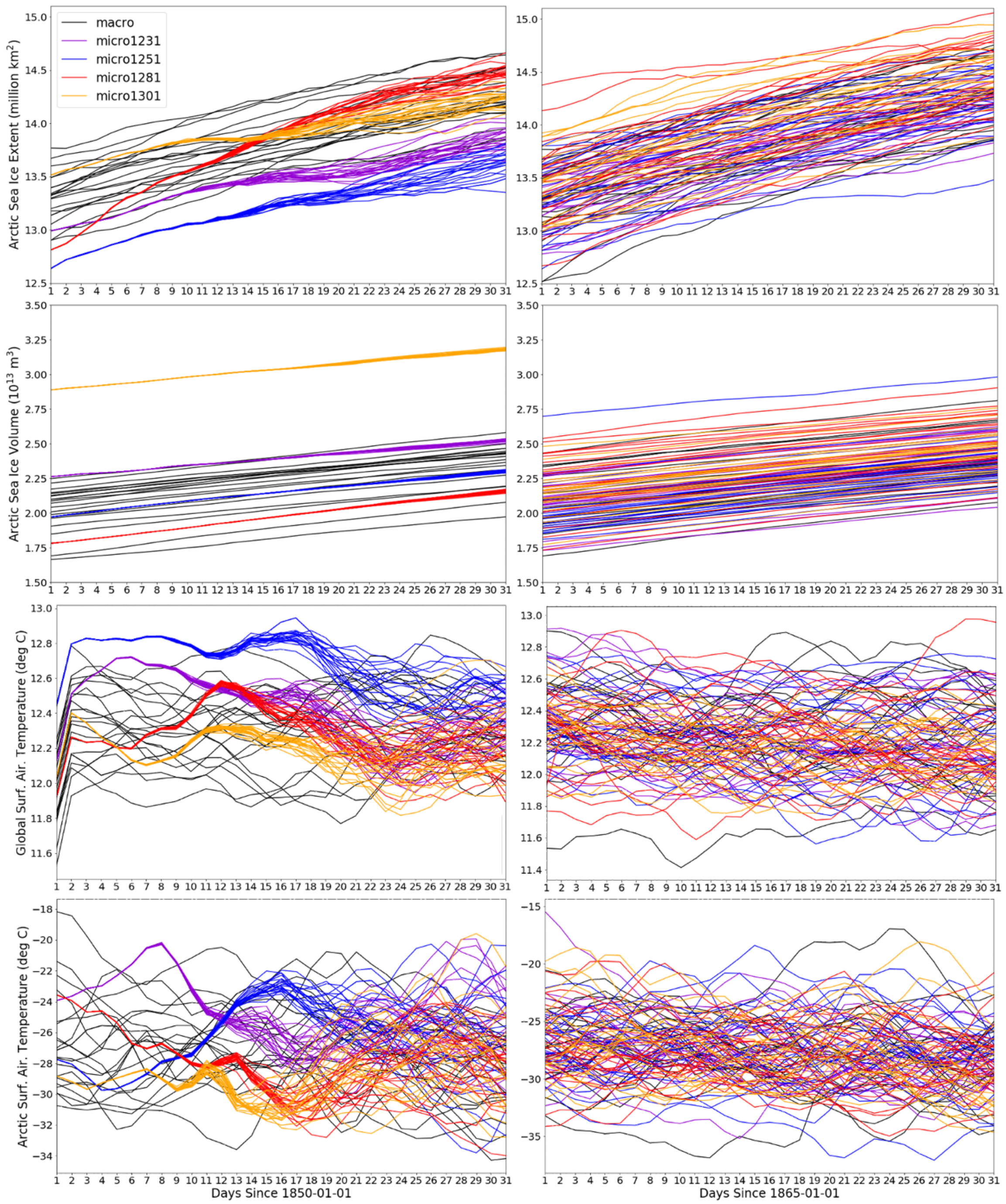

Figure S1. Daily values over the first month (left) and the first month of the 15th year (right) of the CESM2-LE for Arctic sea ice extent, Arctic sea ice volume, Global surface air temperature, Arctic surface air temperature. All 100 members of the CESM2-LE are shown.

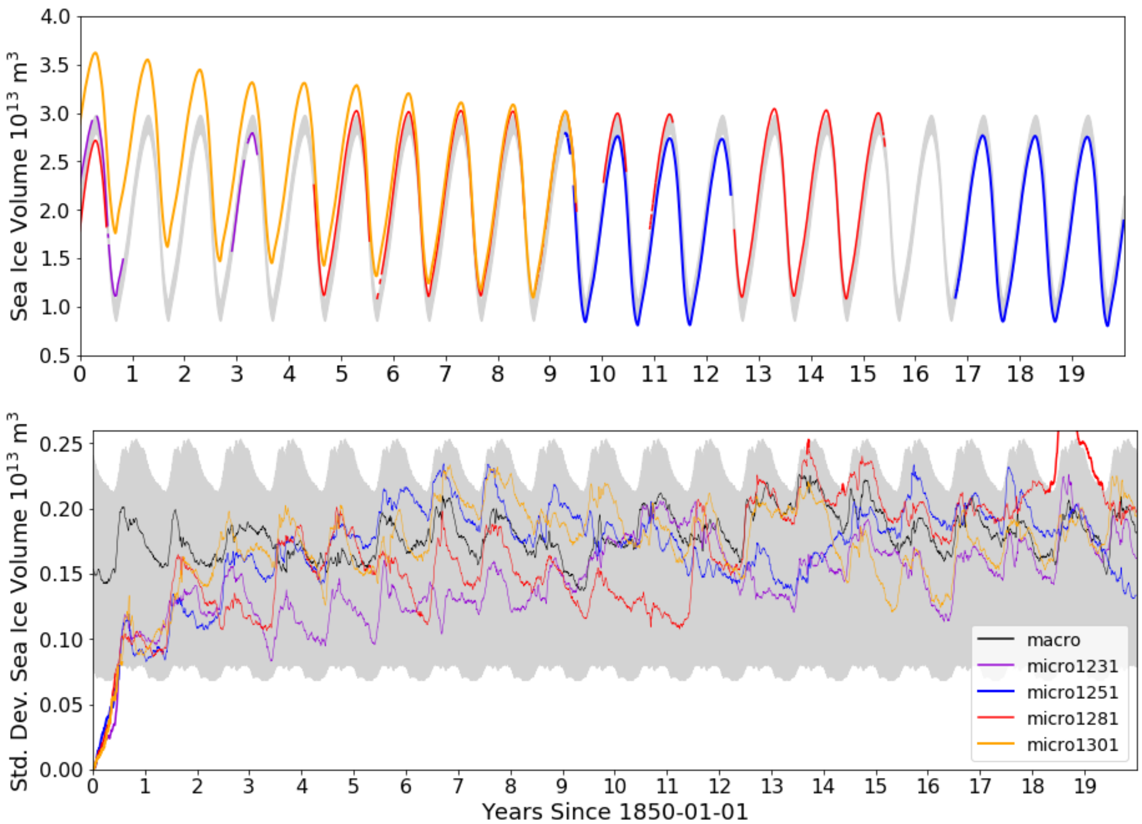

Figure S2. Timeseries of Arctic sea ice volume ensemble mean (top) and standard deviation (bottom) over the first 20 years of the CESM2 large ensemble. Grey shading shows 95% probability of occurrence from bootstrapping the CESM2 pre-industrial control. For the ensemble mean, lines are only plotted when values are statistically different from the pre-industrial control run at the 95% confidence level. For the ensemble standard deviation, thick lines are plotted when values are statistically different from the pre-industrial control run at the 95% confidence level. All 100 members of the CESM2-LE are shown.

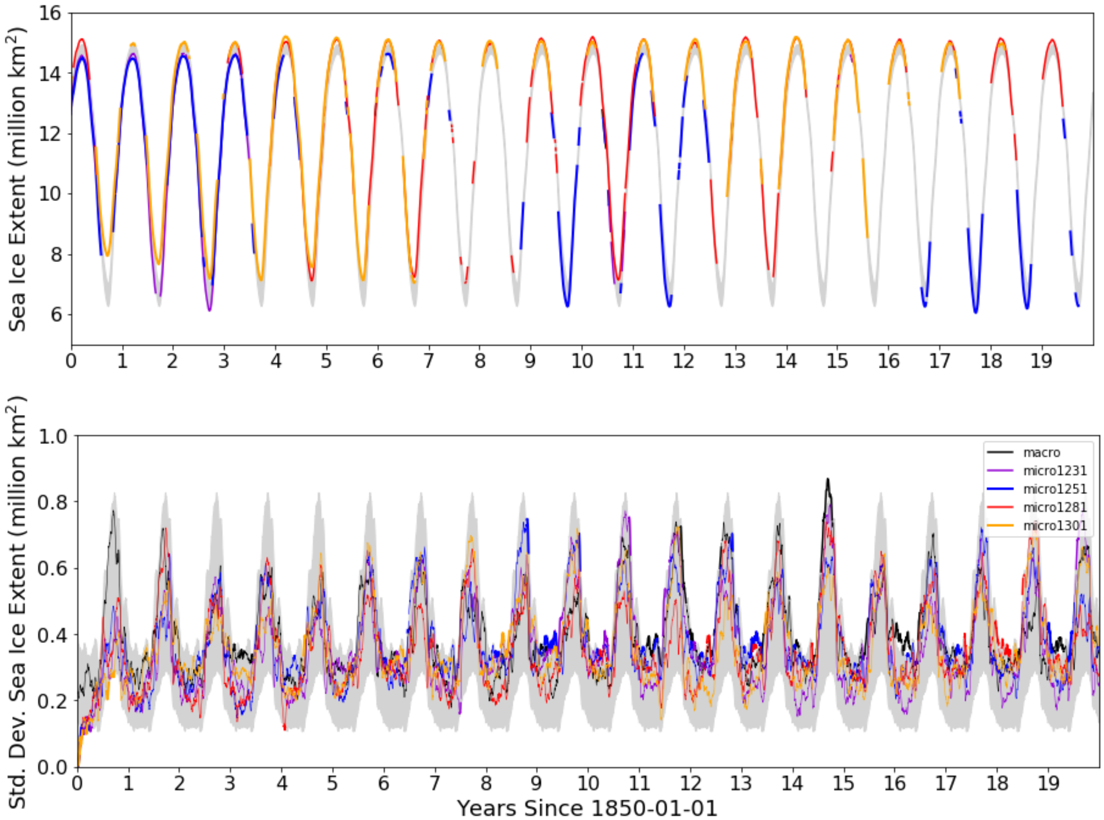

Figure S3. As in Figure S2, but for Arctic sea ice extent.

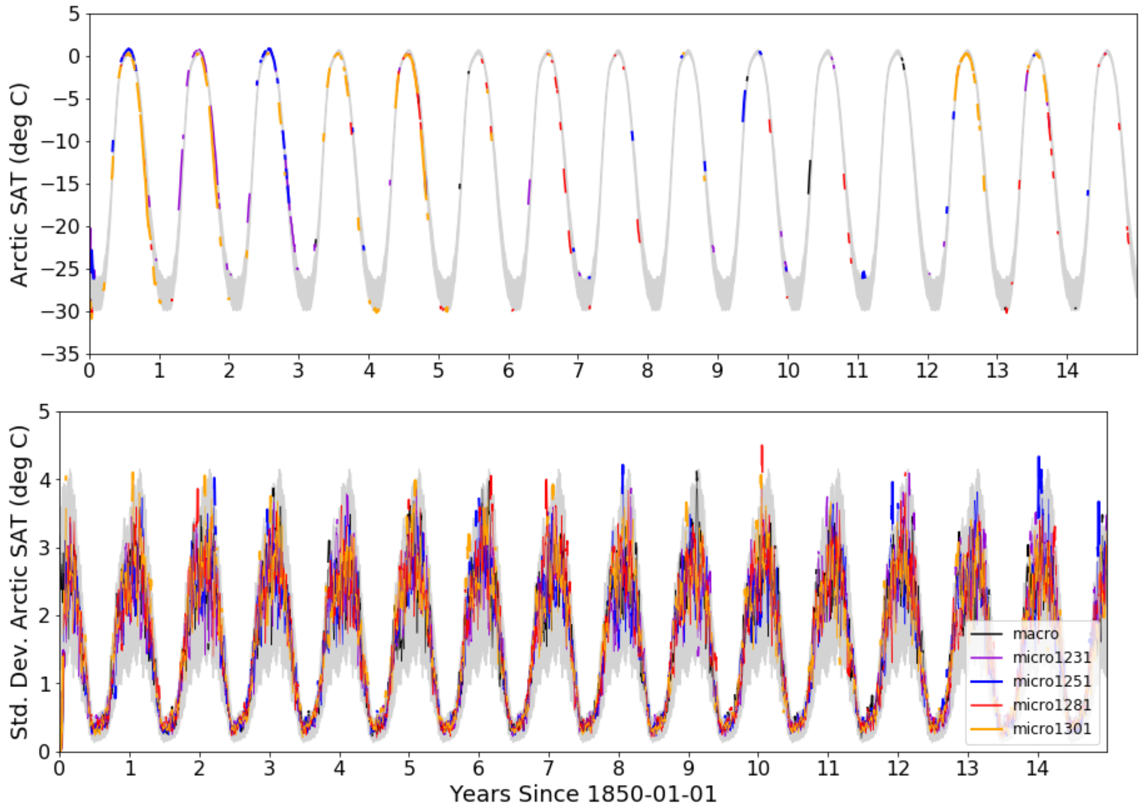

Figure S4. As in Figure S2, but for Arctic surface air temperature.

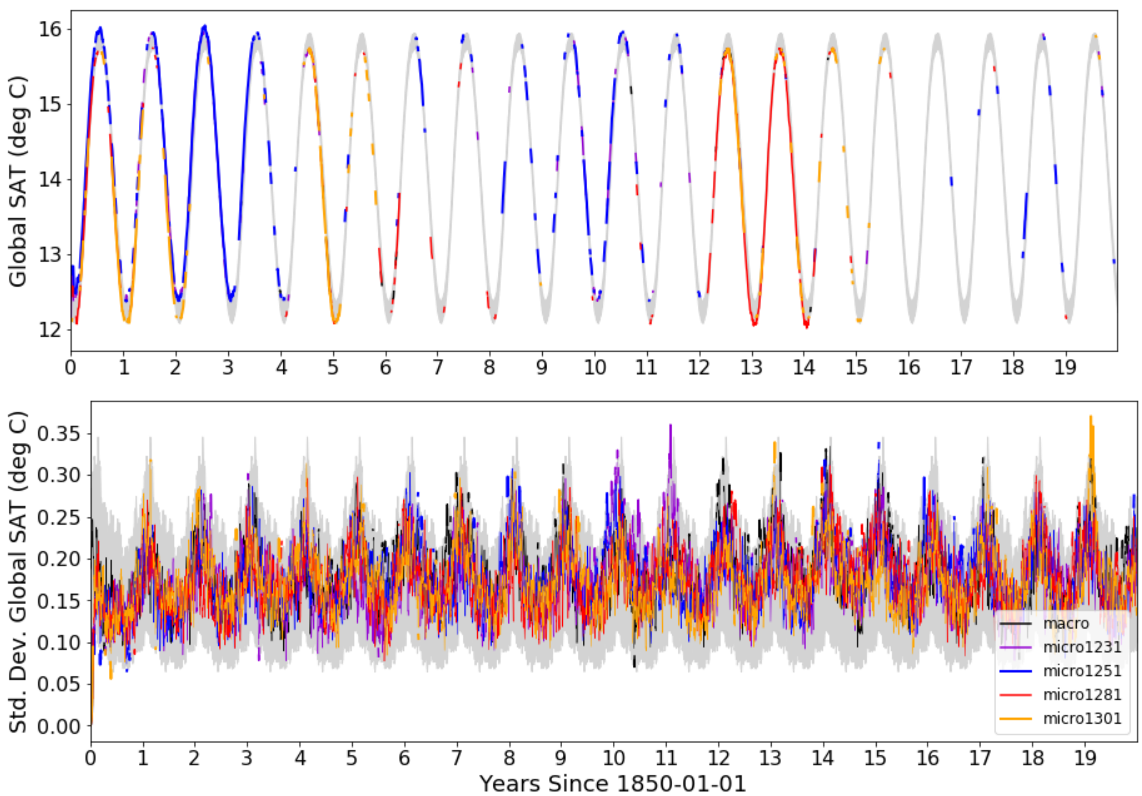

Figure S5. As in Figure S2, but for Global Surface Air Temperature (SAT).

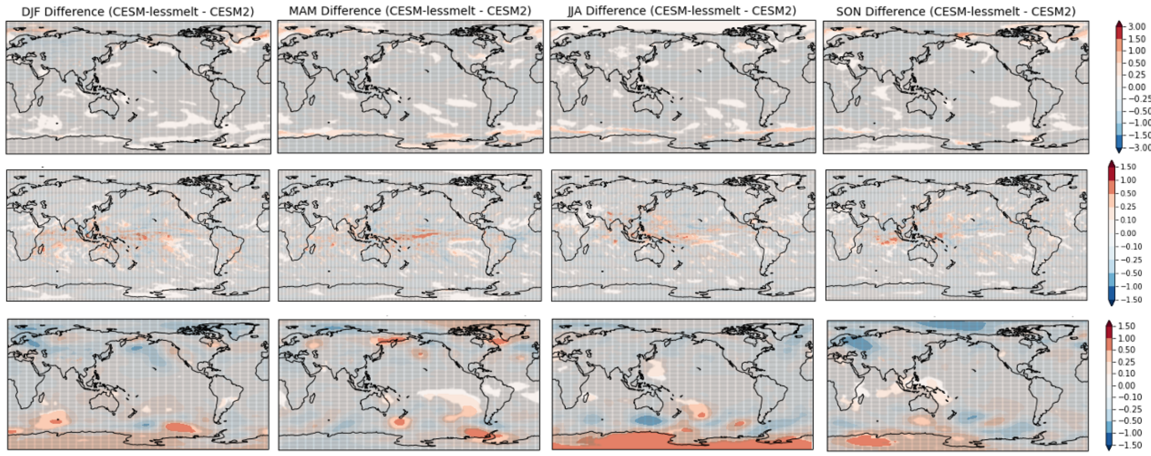

Figure S6. Insignificant differences in variability by season in the 1850 pre-industrial control runs for CESM2 and CESM2-lessmelt: Surface Temperature (K, top row), total precipitation (mm/day, middle row), and sea level pressure (mb, bottom row). All CESM diagnostics for pre-industrial control are here: http://webext.cgd.ucar.edu/B1850cmip6/b.e21.B1850.f09_g17.CMIP6-piControl.001_branch2/, including climate indices in the Climate Variability Diagnostics Package (Phillips et al 2020).

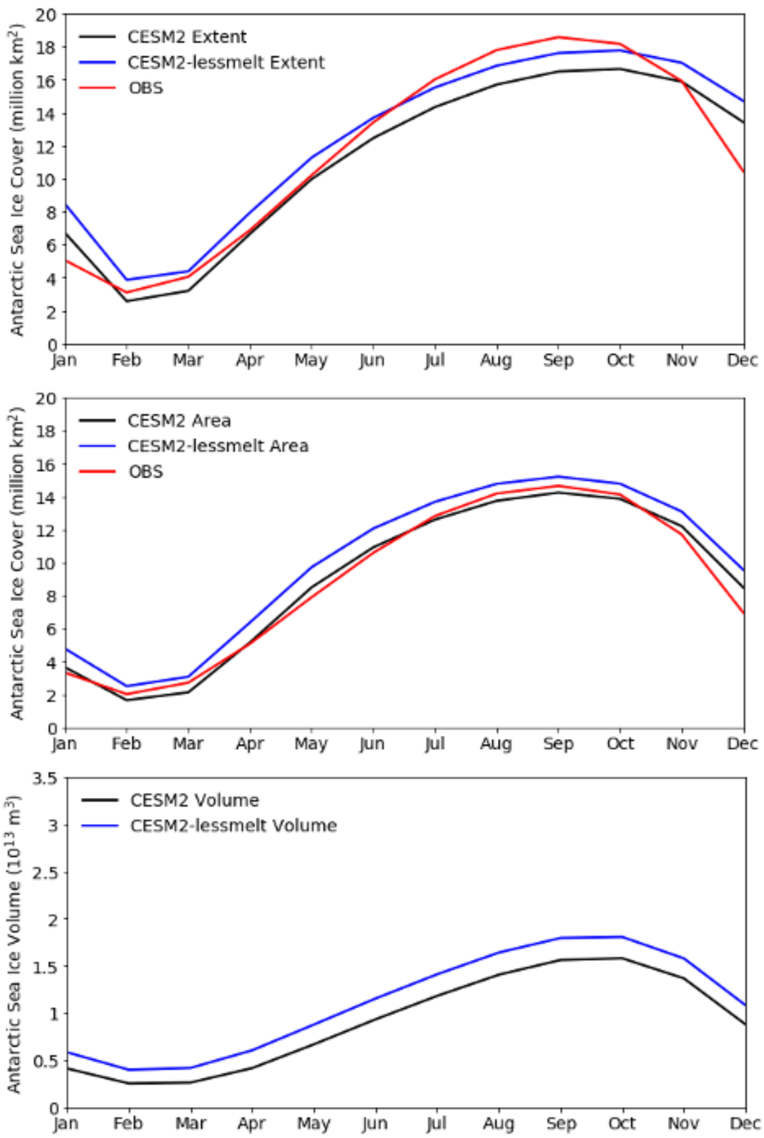

Figure S7. Antarctic present-day (1979-2014) ensemble time mean seasonal cycle in CESM2-LE (members 1-50) and CESM2-tunedice (members 1-4): Sea ice volume (top), Sea ice extent (middle), Sea ice area (bottom). Observations are from NSIDC sea ice index (Fetterer et al. 2017).

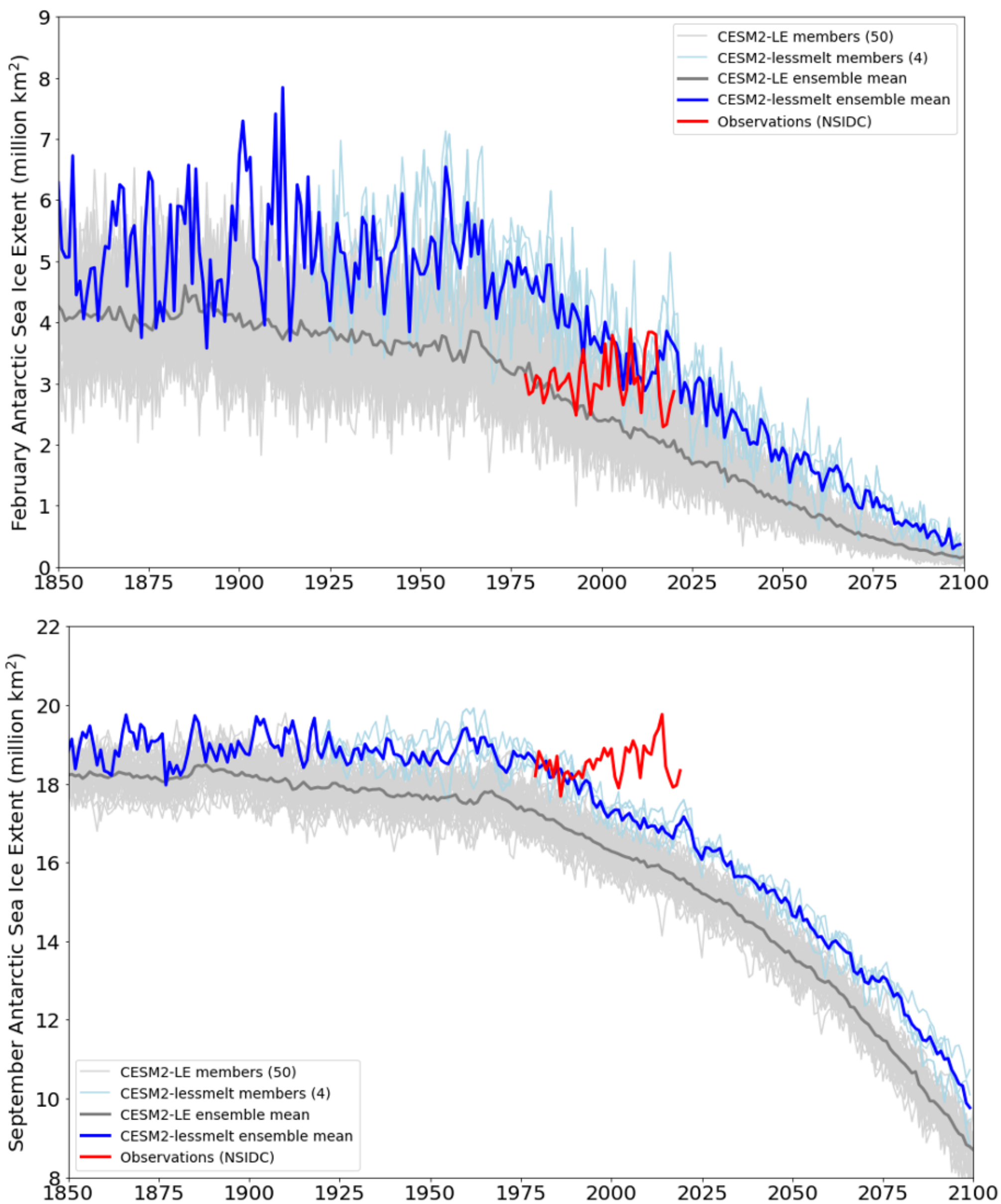

Figure S8. Antarctic sea ice time series comparing CESM2-LE (members 1-50), CESM2-tunedice (members 1-4), and observations in February (top) and September (bottom).

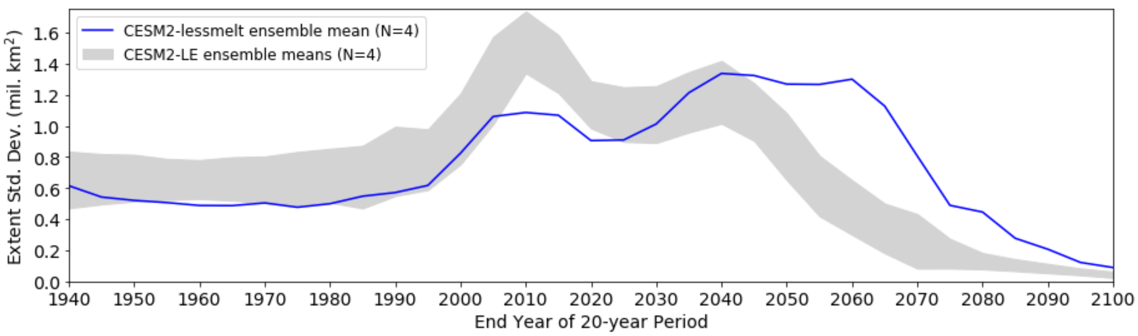

Figure S9. Standard deviation in September sea ice extent in CESM2-LE (members 1-50) and CESM2-tunedice. Grey shading shows 95% confidence intervals on variability calculated by bootstrapping CESM2-LE with 4 members 1,000 times.

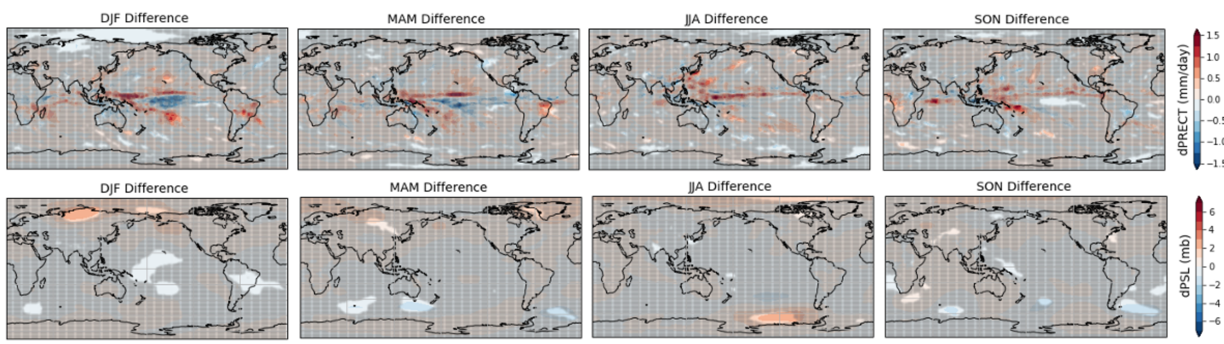

Figure S10. Difference (CESM2-tunedice minus CESM2-LE) in ensemble mean transient climate response (2080-2099 minus 1920-1939) by season: total precipitation (dPRECT, mm/day, top) and sea level pressure (dPSL, mb, bottom). Shading indicates difference is NOT statistically significant at the 95% level. The first 50 members of the CESM2-LE are plotted.