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SUPPLEMENTARY INFORMATION

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Reduced probability of ice-free summers for 1.5 °C compared to 2 °C warming

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Supplementary material

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S.1 Additional ice-free definitions

Ice-free conditions in the Arctic are most commonly defined as the first time the 1 million km^2 threshold is reached or crossed. However, other definitions have also been used. One example is the 2013 IPCC report[1], where ice free conditions were defined as a consecutive 5-year period of September ice extents below 1 million km^2. Using that criteria, the resulting probabilities for ice free conditions in the CESM ensembles are shown in Fig. S.3d, e. For at least a single occurrence of such a 5 year period of ice-free conditions, we find a 100% probability in the RCP8.5 ensemble. In the RCP4.5 simulations, 86% of the ensemble members meet that criteria before the end of the simulations in 2080, and 40% out of the 2.0 °C simulations do so by 2100. None of the 1.5 °C or 1.5 °C OS simulations show even two years of ice-free conditions in a row (0%). Assessing the probability for ice-free conditions at least 5 Septembers in a row for a given year, we find that this probability is also 100% in the RCP8.5 simulations after 2080. For RCP4.5, we find a probability of 25% by the end of the simulations in 2080, while limiting warming to 2.0 °C reduces the probability to only 2.5% at the end of the century. Since the 1.5 °C OS and 1.5 °C simulations never even show two Septembers of ice-free conditions in a row (0%), any occurrence of prolonged ice-free conditions in the 21st century is "extremely unlikely" if warming is limited to 1.5 °C.

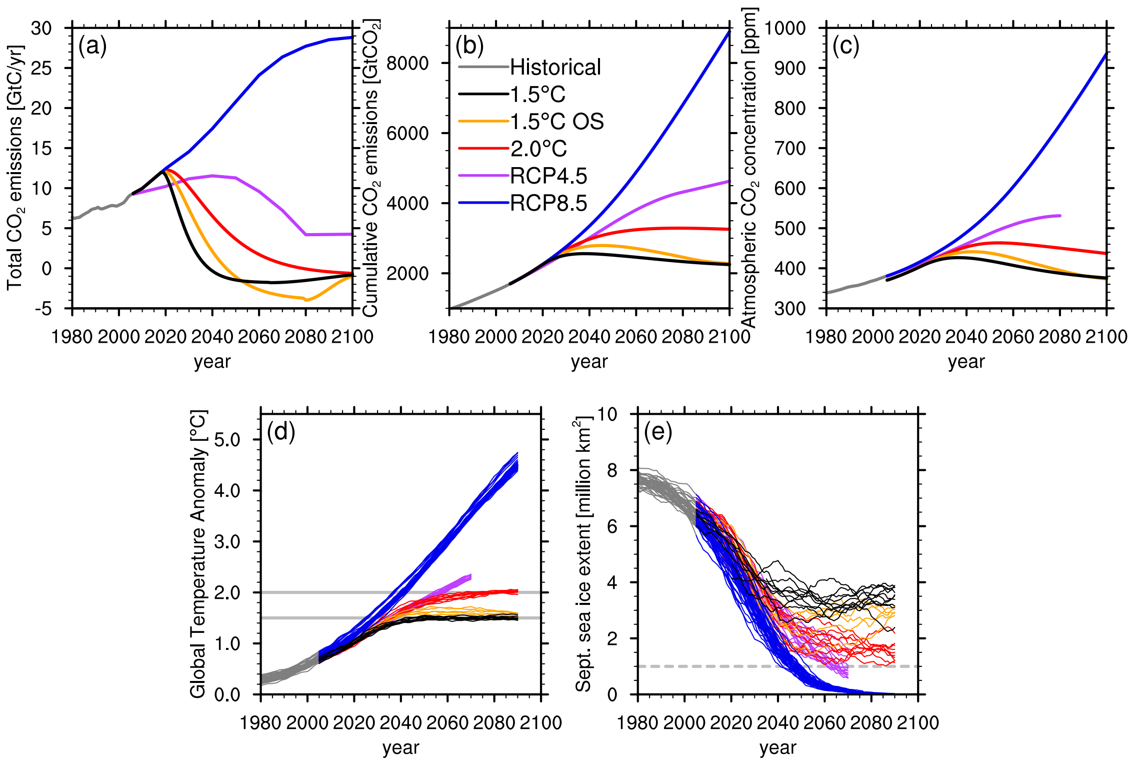

Figure S.1: **Forcing and climate response**: This figure shows (a) the total CO_2 emissions per scenario [in GtC/yr], (b) the resulting cumulative CO_2 emissions since 1850 [in $GtCO_2$], (c) the CO_2 forcing applied in the model [in ppm], (d) the resulting 20-yr running mean annual-mean global temperature anomalies for all ensemble members (relative to pre-industrial, taken as 1850–1920 here), and (e) the resulting 20-year running mean Arctic September sea ice extent for all ensemble members. Solid light grey lines show the low warming temperature thresholds of 1.5 °C and 2.0 °C while dashed light grey lines show the 1 million km^2 ice-free condition threshold. The different scenarios are shown in different colors (RCP8.5 in blue, RCP4.5 in purple, 2.0 °C in red, 1.5 °C OS in orange, 1.5 °C in black).

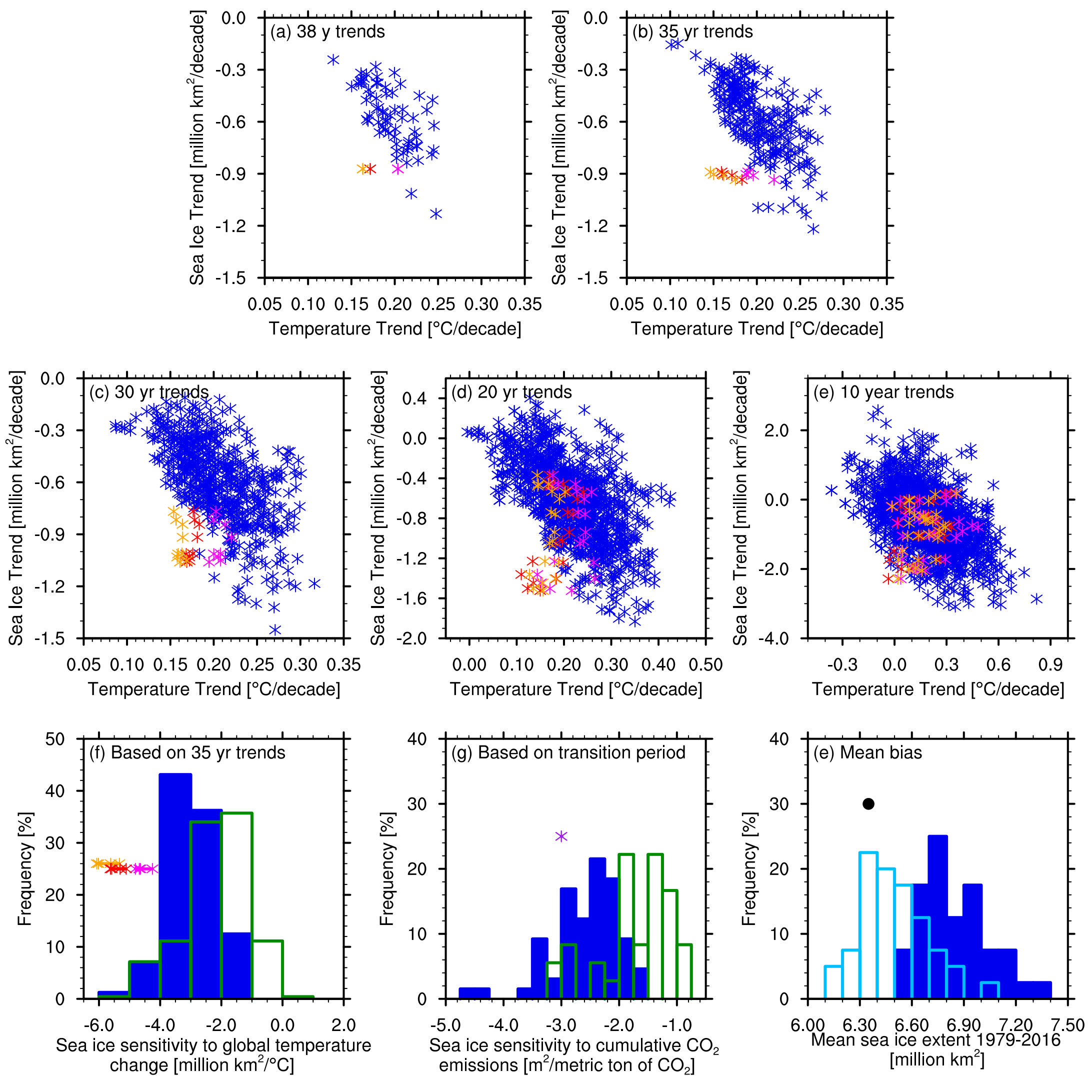

Figure S.2: **Assessment of CESM sea ice simulation:** Sea ice extent trends per decade versus global temperature trends per decade for various trend lengths (a-e) sampled from 1979–2016, in models and observational datasets. The CESM LE is shown in blue. Observational sea ice extent is from the NSIDC[2] and the global surface temperature is the HadCRUT4.5 data[3,4] (red), the GISS data[5,6] (magenta), and the NCDC temperature[7,8] (orange). (f) shows the frequency distribution of the sea ice sensitivity to global warming, calculated as ratio of the 35 year sea ice extent trends and the 35 year global annual mean temperature trends, following the method used in[9,10,11]. Histograms for the CESM LE (blue) and the CMIP5 models (green)[11] are included, as well as observational estimates using the same colors as in (a–d). (g) shows the histogram of the sea ice sensitivity to cumulative CO_2 emissions, calculated in the CESM LE (blue) following[12] and the CMIP5 distribution from Notz and Stroeve[12] in green. It also shows the single observational estimate from Notz and Stroeve[12] as purple marker on the histogram. (e) shows the mean sea ice extent for 1979–2016 in the CESM ensembles (blue) compared to the mean NSIDC[2] 1979–2016 September sea ice extent (black marker). The light blue histogram in (e) shows the mean sea ice extent histogram if shifted by -0.35 million km^2 to place the observations in the most likely bin, with the effect on the calculated probabilities shown in Fig. S.3

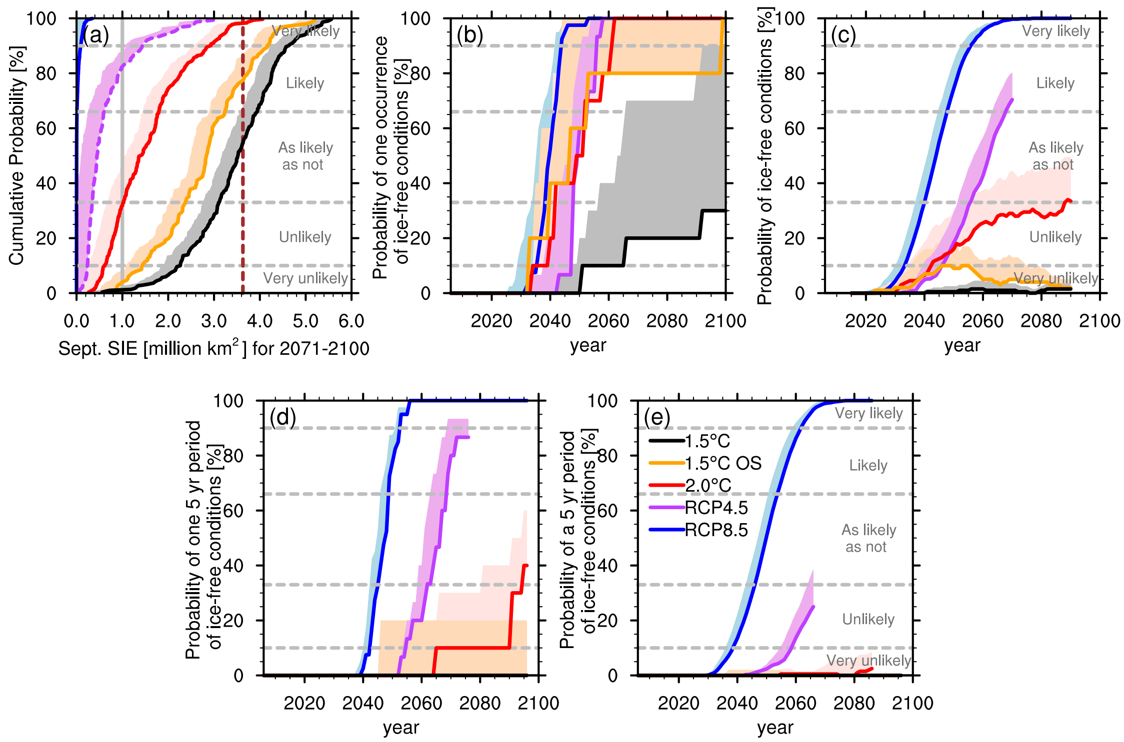

Figure S.3: **Additional probabilities:**(a-c) the solid lines show the same probabilities as shown in Fig. 1, but now with additional shading indicating the possible uncertainty of these probabilities due to CESM September mean being biased high over 1979–2016 (RCP8.5 in blue, RCP4.5 in purple, 2.0 °C in red, 1.5 °C OS in orange, 1.5 °C in black). This uncertainty assumes that the observations fall within the most likely 1979–2016 mean sea ice extent bin from the CESM large ensemble, which means shifting all September sea ice extents by −0.35 million km^2 (as shown in Fig. S.2e). (d-e) shows the same probabilities as in b and c, but for 5-year consecutive ice-free conditions in September, with the shading showing the possible uncertainty range due to the mean bias, as in (a-c).

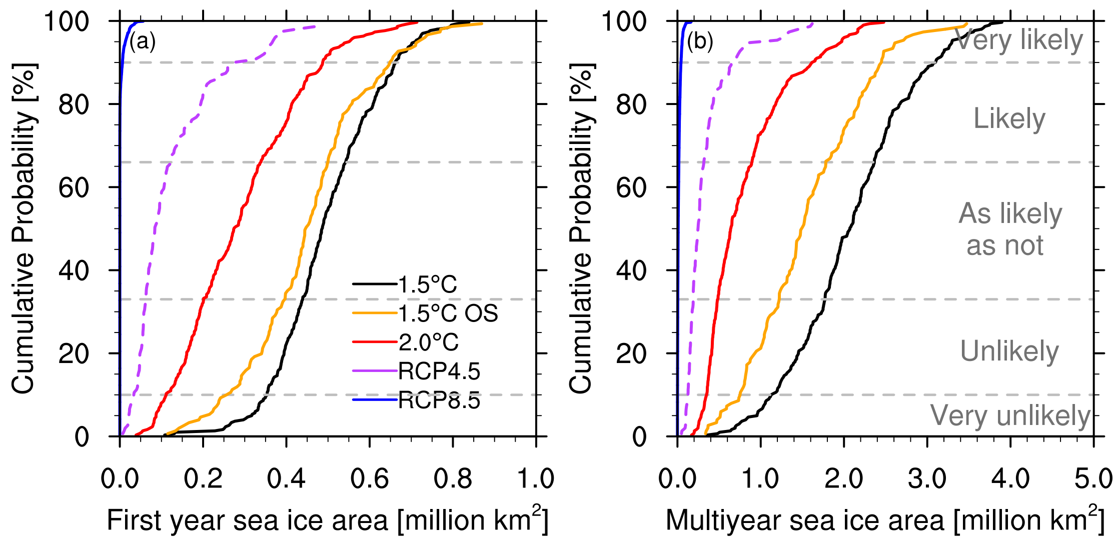

Figure S.4: **First year and multi-year sea ice:** Probabilities of (a) first-year and (b) multi-year sea ice area in the Arctic to be below a given value for different scenarios, for 2071–2100. Different scenarios are shown in different colors (RCP8.5 in blue, RCP4.5 in purple, 2.0 °C in red, 1.5 °C OS in orange, 1.5 °C in black). Note that for the RCP4.5, only years up to 2080 are used, as these simulations end in 2080. The RCP4.5 results are therefore shown as dashed line.

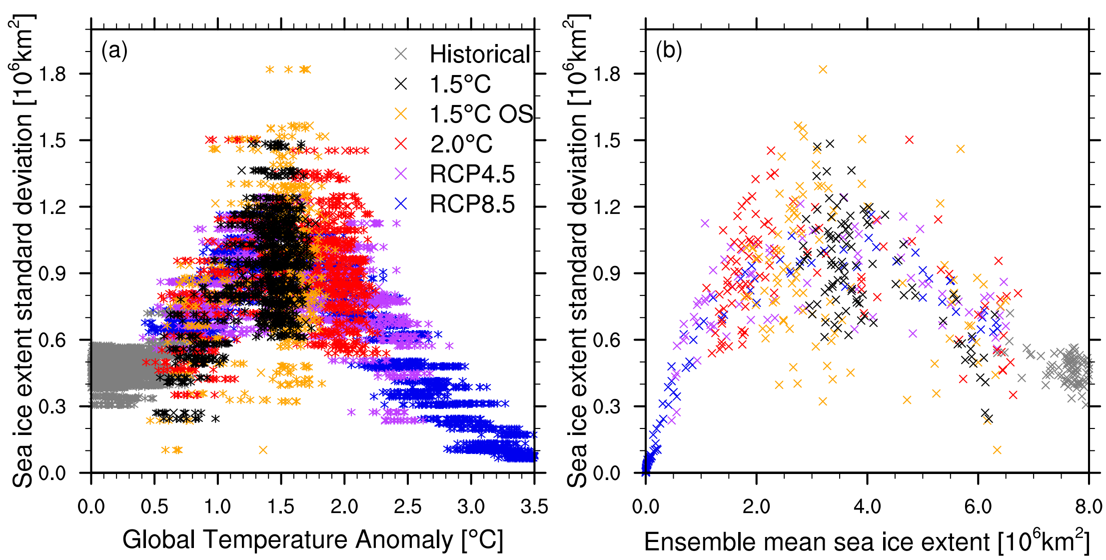

Figure S.5: **Change in the standard deviation of September sea ice extent** as function of (a) global mean temperature anomaly (relative to pre-industrial, 1850-1920) and (b) ensemble mean sea ice extent for all CESM ensembles from the different scenarios (color coded with RCP8.5 in blue, RCP4.5 in purple, 2.0 °C in red, 1.5 °C OS in orange, 1.5 °C in black).

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