Reduced probability of ice-free summers for 1.5 °C compared to 2.0 °C warming

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Abstract

Arctic sea ice has declined rapidly with increasing global temperatures. However, it is largely unknown how Arctic summer sea ice impacts would vary under the 1.5 °C Paris target compared to scenarios with greater warming. Using the Community Earth System Model (CESM), I show that constraining warming to 1.5 °C rather than 2.0 °C reduces the probability of summer ice-free conditions by 2100 from 100% to 30%. It also reduces the late-century probability of an ice cover below the 2012 record minimum from 98% to 55%. For warming above 2 °C, frequent ice-free conditions can be expected, potentially for several months per year. Although sea ice loss is generally reversible for decreasing temperatures, sea ice will only recover to current conditions if atmospheric CO_2 is reduced below present-day concentrations. Due to model biases, these results provide a lower bound on summer sea ice impacts, but clearly demonstrate the benefits of constraining warming to 1.5 °C.

Summer Arctic sea ice area loss has been shown to exhibit a linear relationship with 20–30 year running means of rising global mean temperatures[1,2,3,4,5,6,7], atmospheric CO_2 concentrations[8,9,5], and cumulative CO_2 emissions[10], in both observations and model simulations. Using these emergent constraints, a summer ice-free Arctic is projected to occur for as little as an additional 1 °C warming above 1980–99 global temperatures[7] or for additional emissions of 1000 $GtCO_2$ above 2015 levels[10]. But what does that mean for summer Arctic sea ice if global warming stabilizes at 1.5 °C or 2.0 °C above pre-industrial conditions (taken as 1850–1920 here), as proposed in the Paris IPCC agreement[11]? Most previous studies of summer Arctic sea ice loss can not answer that question, as they have focused on the medium to high emission scenarios, with generally much larger warming than 1.5 °C by 2100[12,13,14,15,16,17,18]. Two exceptions exist, but only for the probability of ice-free conditions in the Arctic. Screen and Williamson[19] looked at the existing CMIP5 simulations to determine the probability of an ice-free Arctic (i.e., sea ice extent of 1 million km^2 or less) under the IPCC low-warming targets. However, they investigated the sea ice evolution only until the year before annual global mean temperature anomalies first crossed the 1.5 °C, 2.0 °C, and 3 °C thresholds in the RCP simulations. Sanderson et al.[20] assessed the probability of ice-free conditions in a given September using dedicated low-warming (1.5 °C and 2.0 °C) ensemble simulations with the CESM. Here we answer the more comprehensive question of how the Arctic summer sea ice cover is impacted by limiting warming to the IPCC targets compared to larger warming within the 21st century. For that purpose, we use five CESM1.1 ensembles[21,22,20], forced by traditional medium (RCP4.5) and high (RCP8.5) emission scenarios as well as dedicated low warming scenarios. These simulations are called 1.5 °C, 1.5 °C overshoot (OS), 2.0 °C, RCP4.5, and RCP8.5 in the following and lead to global mean warming of 1.5 °C to over 4 °C by the year 2100 (see Methods section and Fig. S.1 for more details).

We show that limiting warming to 1.5 °C rather than 2.0 °C decreases the probability of September sea ice extents below the 2012 minimum from 98% to 55% at the end of the 21st century. We also show that sea ice extent does not recover at the same rate as it is lost when CO_2 concentrations or cumulative CO_2 emissions decrease rather than increase. In terms of ice-free conditions, we find that the probability of at least one occurrence of ice-free conditions in September is reduced to 30% if warming is limited to 1.5 °C, rather than 100% for 2.0 °C warming or greater. These probabilities of ice-free conditions under the low-warming targets are much higher than those found previously by Screen and Williamson[19]. This is despite the fact that the CESM provides a conservative estimate of future Arctic sea-ice loss, as it has a positive mean bias in September sea ice extent, and its sea ice sensitivity to warming is on the low end compared with observations (but higher than many CMIP5 models[23], see Methods section and Fig. S.2 and S.3 for details). Nevertheless, limiting warming to 1.5 °C rather than 2.0 °C or more has the potential to avoid frequent ice-free conditions as well as prevent a loss of multi-year sea ice in the Arctic. This matters for more than just preserving sea ice, given the importance of summer sea ice for marine mammals such as polar bears[24,25,26,27] as well as for coastal erosion along the Arctic coast[28,29].

Results

September sea ice cover in the late 21st century

We find that even by limiting warming to 1.5 °C, the Arctic summer sea ice cover experiences significant reductions compared to today (Fig. 1a). By the end of the 21st century, 55% of the September sea ice extents are below the record minimum to date (in 2012[30,31]). However, if warming reaches 2.0 °C, September sea ice extent will be below the record 2012 minimum 98% of the time by the late 21st century (Fig. 1a). For even larger warming, the Arctic sea ice cover will be in a completely different regime than we know so far by the end of the century, with September sea ice extents far below those observed over the last 38 years, including a high probability of ice-free conditions (Fig. 1a). This large reduction in September ice extent also affects the presence of multi-year sea ice (see Fig. S.4), which is strongly reduced as less ice survives the melt season.

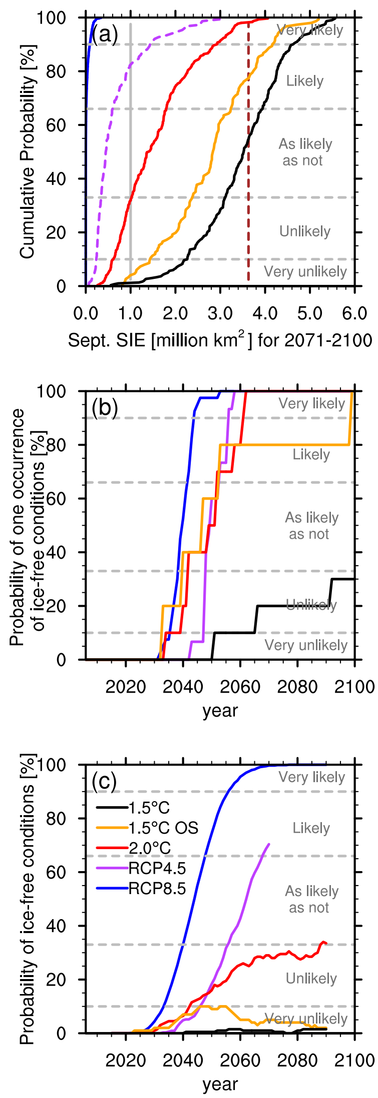

Figure 1: **Probabilities of September sea ice characteristics:** (a) Probabilities of late 21st century (2071–2100) September sea ice extents, showing how likely it is that sea ice extents are below a given threshold for different scenarios (RCP8.5 in blue, RCP4.5 in purple, 2.0 °C in red, 1.5 °C OS in orange, 1.5 °C in black). For example, it shows how likely it is for the September sea ice extent to be below the minimum monthly-mean September ice extent of 3.63 million km^2 observed to date (in 2012, based on the NSIDC sea ice extent[30], shown by the dashed vertical brown line), or below the "ice-free" Arctic threshold of 1 million km^2 (shown by the vertical solid grey line). For RCP4.5, the probabilities are for 2071-2080 only, due to the end of the simulations in 2080. RCP4.5 is therefore shown as dashed line. (b) Probabilities of reaching an ice-free Arctic at least once as function of time as well as (c) the probability of ice-free conditions in a given year (using a 20-yr running mean), using the same colors as in (a). All probabilities are based on the CESM ensemble simulations. The meaning of the probabilities is given in grey according to the IPCC convention[32]. Panel (c) is adapted from Sanderson et al.[20], where only the probabilities for the three low warming scenarios were shown.

Probabilities of an ice-free Arctic by 2100

We find a 100% probability of ice-free conditions occurring at least once by 2100 for all of the scenarios except 1.5 °C (Fig. 1b). In the IPCC language[32], that means at least one ice-free September in the Arctic is "extremely likely" if warming reaches or exceed 2.0 °C. In contrast, in the 1.5 °C ensemble, there is only a 30% probability of ice-free conditions occurring at least once if warming is limited to 1.5 °C, which makes it "unlikely" in the IPCC language.

Notably, for scenarios where warming is limited to 1.5 °C and 2.0 °C, the probabilities found here are much higher than those found by Screen and Williamson[19] in CMIP5 simulations: 30% versus 0% for 1.5 °C warming and 100% versus 35% for 2.0 °C warming. If we account for the fact that the CESM has a positive mean bias in its 1979–2016 September sea ice extent, the probability of at least one occurrence of ice-free conditions reaches 90%, even if warming is limited to 1.5 °C (Fig. S.3b), further enhancing the difference to the 0% probability found in Screen and Williamson[19]. This large difference in the projected probability of ice-free conditions under the low-warming IPCC targets is due to important differences in the analysis performed. Screen and Williamson[19] assessed the probability of an ice-free Arctic in the CMIP5 RCP8.5 and RCP4.5 simulations before 1.5 °C and 2.0 °C of global warming were first reached. We assessed the probabilities of at least one occurrence of ice-free conditions, in simulations that have a 30 year ensemble-mean that remains just below these low-warming temperatures for several decades (see Fig. S.1d). As these simulations have several decades of mean temperatures at these thresholds, internal variability leads to temperature and sea ice variability around the ensemble mean. That can cause ice-free conditions to occur at these lower global mean temperatures, despite the absence of ice-free conditions in the transient evolution to these temperatures. Hence, we find much higher probabilities of an ice-free Arctic compared to Screen and Williamson[19]. If the goal of limiting warming to 1.5 °C or 2.0 °C is achieved, it seems very likely that temperatures would stay at those levels for a period of time, rather than decrease below them immediately. Hence, the probabilities found here for the low-warming scenarios correspond more directly to those we might observe during the 21st century if these targets can be achieved. These

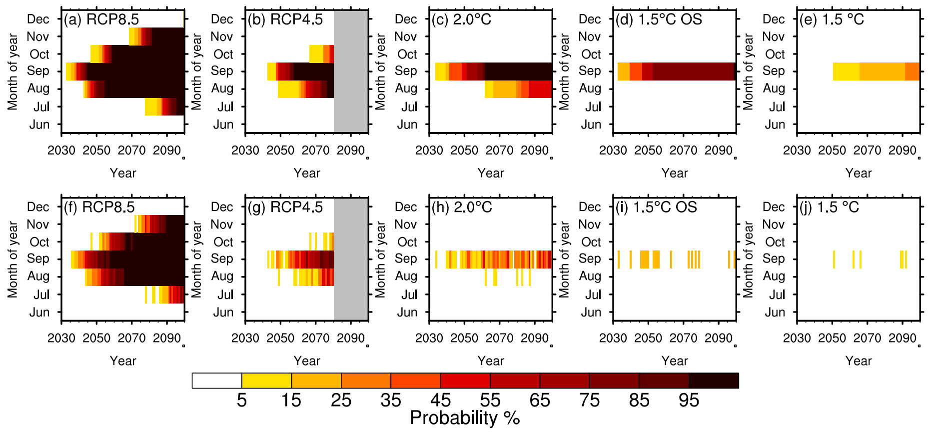

Figure 2: **Probability of ice-free conditions in a given month**, for at least one occurrence of ice-free conditions per month in the different ensembles (first column, a–e) as well as the probability of a given month being ice-free in a given year (second column, f–j). These panels show when ice-free conditions could occur during the year (a–e) and how long the ice-free season could potentially be in the late 21st century (f–j) under different forcing scenarios. The grey shading indicates no data, due to the end of the RCP4.5 simulations in 2080.

results highlight the importance of employing dedicated simulations for the low warming IPCC targets to assess the likelihood of climate extremes, rather than sub-sampling the existing higher warming scenarios on the way to these target temperatures,[20,33].

For a given year, Sanderson et al.[20] showed that the probabilities of ice-free conditions in September are also much reduced if warming is limited to 1.5 °C (2%) rather than to 2.0 °C (34%) or greater (Fig. 1c). However, it is not only the overall probabilities of ice-free conditions that differ between scenarios, but also the months during which these conditions might occur (see Fig. 2). Ice-free conditions occur exclusively in September in the 1.5 °C and 1.5 °C OS simulations, if they occur at all. In the 2.0 °C simulations, a few instances of ice-free conditions also occur in August, in addition to a 100% probability in September by the end of the century. In the RCP4.5, ice-free conditions occur at least once in August and September in all ensemble members and in October for several members. Under RCP8.5, the ice-free season in the Arctic could extend from July to November in some years, with a 100% probability of ice-free conditions from August to November by the last decade of the 21st century (Fig. 2f).

Timing of the first possible ice-free Arctic

The timing of the first possible occurrence of an ice-free Arctic in September is strongly impacted by internal variability. In particular, we find that one of the 1.5 °C simulations reaches ice-free conditions two years before the last of the RCP8.5 simulations does (2050 and 2053, respectively; see Fig. 3a), despite very different mean ice states and overall probabilities of an ice-free Arctic during the 21st century. This is due to enhanced internal variability in the low-warming scenarios, as their mid-century September sea ice extents are close to the peak of the ice extent standard deviation (around 3.5 million km^2 and 1.4 °C global mean warming, see Fig. S.5). This enhanced internal variability leads to first ice-free conditions occurring at global temperature anomalies as low as 1.4 °C in one of the 1.5 °C ensemble members (Fig. 3b), even though the CESM ensemble mean temperature at which ice-free conditions occur for the first time is 1.9 °C. Hence, the probability of an early ice-free Arctic increases the stronger the forcing is, as the mean ice extent will be closer to the 1 million km^2 threshold in a warmer climate, so small changes can lead to ice-free conditions. At the same time, a first occurrence of ice-free conditions could occur early despite a reduced forcing, due to the peak of the internal variability at global temperature anomalies around 1.4 °C. However, in the low warming scnearios it would likely be an isolated event, whereas in stronger warming scenarios a second ice-free year would soon follow the first (see section S1. and Fig. S.3d). The largest impact of scenario differences on the timing of the first possible occurrence of an ice-free Arctic in September is again found for limiting warming to 1.5 °C rather than 2.0 °C (Fig. 3a). This means that limiting warming to 1.5 °C is likely to delay ice-free conditions in September, and could altogether avoid them.

Due to the enhanced internal variability in the low warming scenarios, the prediction uncertainty for the first occurrence of ice-free conditions is over six decades if we consider all scenarios investigated here (Fig. 3a). This is a significant change to the prediction uncertainty of two decades for the RCP8.5 simulations due to internal variability alone[18]. Furthermore, previous work has shown that ensembles with five to ten members on average only exhibit 50-60% of the ensemble spread of a 40 member ensemble[18]. Hence, the uncertainty range of over six decades may underestimate the full ensemble spread due to the 5–10 member low warming ensembles. In particular, it is conceivable that all 1.5 °C ensemble members would cross the ice-free threshold at least once if they were continued for longer at a mean global temperature anomaly of 1.5 °C, due to the enhanced internal variability of the September ice extent in these simulations.

Sea ice evolution under decreasing CO_2 emissions

We find that the linear relationship between sea ice extent and temperature is independent of the direction or rate of the forcing change. In contrast, we find that sea ice does not recover at the same rate as it is lost for CO_2 concentrations or cumulative emissions change (Fig. 4). This hysteresis-like behavior occurs because the linear relationship between CO_2 and September sea ice extent breaks down once CO_2 emissions and/or concentrations decrease or stabilize and the climate begins to equilibrate with the forcing[5]. As the long-term global temperature change ultimately controls the sea ice extent, the linear relationship between annual mean global temperature and September sea ice extent stays the same even as the CO_2 concentrations or cumulative emissions stabilize or decrease (Fig. 4c).

Hence, if temperatures should eventually decline again, sea ice will increase at the same rate per °C as it was lost. This potential for a recovery of sea ice when temperatures decline is shown in the the 1.5 °C OS simulation, and agrees with previous work on the reversibility of Arctic sea ice loss[34,4,5]. However, to return sea ice to present-day conditions, the atmospheric CO_2 concentrations need to be reduced below current values.

Conclusions

Using output from five ensembles with the CESM[21,22,20] that range from 1.5 °C to over 4 °C global warming by 2100 (relative to 1850–1920), we investigated the question of how much reduced emissions, and hence warming, matters for Arctic summer sea ice in the mid-to-late 21st century. We find that limiting warming to 1.5 °C has a large impact for summer Arctic sea ice. If warming is limited to 1.5 °C, September sea ice extents

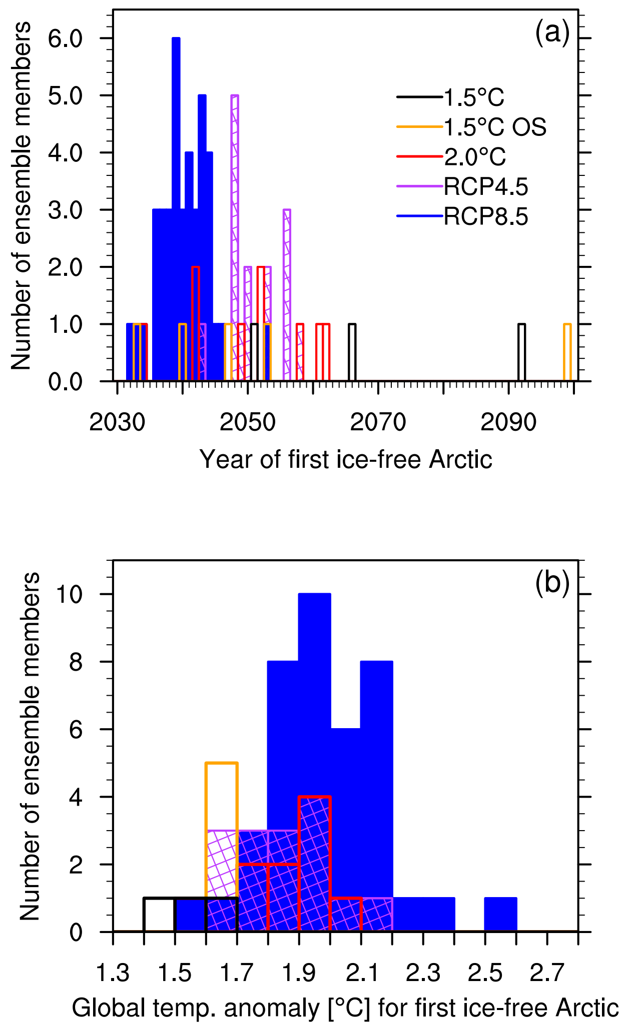

Figure 3: **First ice-free conditions for different scenarios**: (a) Histogram of the first year of ice-free conditions in September for each ensemble member, color coded by the different scenarios (RCP8.5 in blue, RCP4.5 in purple, 2.0 °C in red, 1.5 °C OS in orange, 1.5 °C in black). This panel is an adaptation from Jahn et al.[18], which showed only RCP8.5 and RCP4.5. (b) Histogram of the global temperature anomaly [°C] in the year during which these first ice-free conditions occur in each ensemble member, with the same color coding as panel (a).

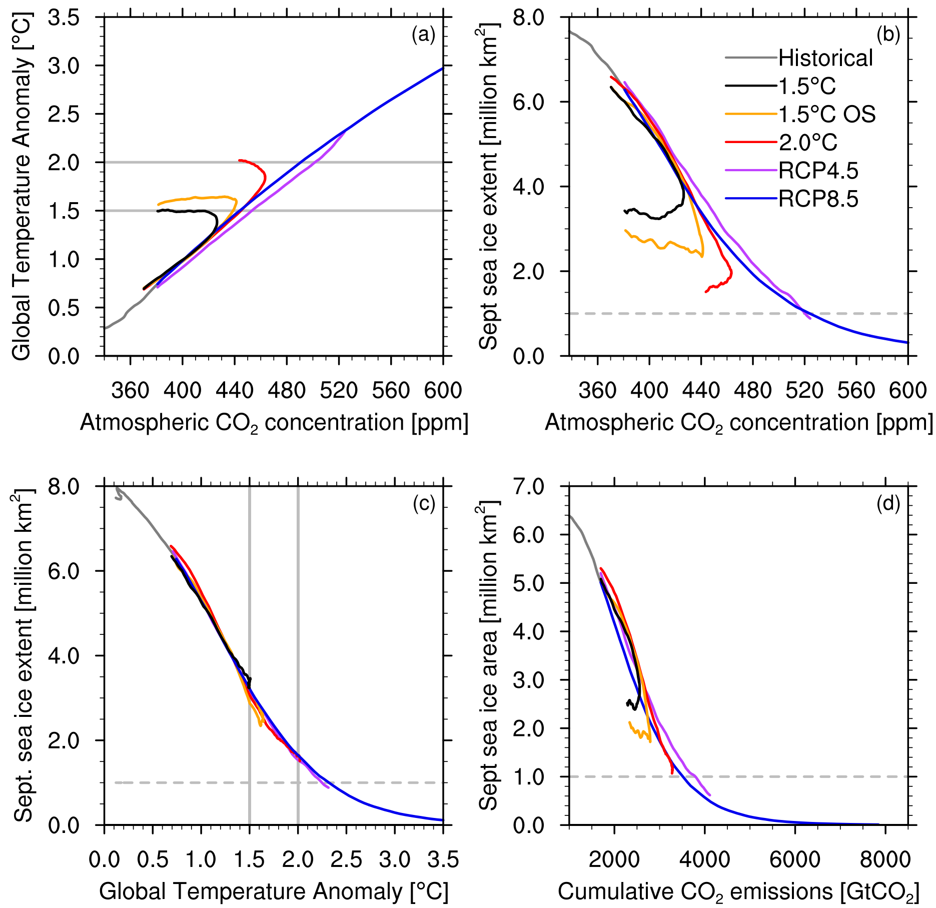

Figure 4: **Linear relationships**: (a) 20-year running ensemble mean global temperature anomaly as function of the atmospheric CO_2 concentration, (b) 20-yr running ensemble mean September sea ice extent as function of the atmospheric CO_2 concentration, (c) 20-year running ensemble mean September sea ice extent as function of the 20-year running ensemble mean global temperature anomaly, and (d) the 20-year running ensemble mean September sea ice area as function of the cumulative CO_2 emissions since 1850, for all scenarios (RCP8.5 in blue, RCP4.5 in purple, 2.0 °C in red, 1.5 °C OS in orange, 1.5 °C in black). 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.

below the record 2012 minimum occur only 55% of the time in the late 21st century, as compared with 98% if warming is limited to 2.0 °C, and 100% of the time under the higher emission scenarios (RCP4.5 and RCP8.5). Furthermore, if warming is limited to 1.5 °C, the probability for any occurrence of ice-free Septembers by 2100 is only 30%, as opposed to 100% for warming of 2.0 °C or greater. Under scenarios reaching or exceeding 2.0 °C, ice-free conditions for multiple summer months and for several years in a row also become possible by the late 21st century. Notably, the probabilities we find for any occurrence of ice-free conditions if warming is limited to 1.5 °C and 2.0 °C are much higher than found by Screen and Williamson[19] in CMIP5 simulations – 30% versus 0% for 1.5 °C warming and 100% versus 35% for 2.0 °C warming. This difference arises from analyzing dedicated ensembles for low emission scenarios that equilibrate at these low warming targets, rather than analyzing only the transient evolution until just before these global mean temperatures are first reached. This shows that using dedicated low-warming simulations is the preferred method to assess the likelihood of extreme events under the low-warming scenarios, due to the large impact of internal variability, in particular on extreme events.

While the CESM is just one model, the availability of ensembles for five different scenarios for the 21st century with the same model allows a robust assessment of probabilities of the sea ice evolution in the context of internal variability and scenario differences. In order to test the impact of a slightly high mean bias in the average CESM 1979–2016 September sea ice extent (Fig. S.2e), all calculations were repeated with a shifted sea ice extent (Fig. S.3 and Methods section). That analysis shows that all quoted probabilities are higher if assessed from the shifted ice extents, but none of the results change qualitatively. In particular, the large difference for Arctic summer sea ice between limiting warming to 1.5 °C versus 2.0 °C remains.

The timing of a first possible occurrence of an ice-free Arctic in September is strongly impacted by internal variability, rather than being clearly dominated by the forcing. Nonetheless, limiting warming to 1.5 °C rather than 2.0 °C or more would likely delay the first occurrence of an ice-free Arctic, and could avoid it altogether. Despite this, an ice-free Arctic could occur rather early even under low future emissions, in particular because the internal variability is enhanced at ice extents around 3.5 million km^2 and temperature anomalies of 1.4 °C. How frequently an ice-free Arctic re-occurs after the first time, however, is strongly dependent on the emission pathway.

We also find that the linear relationship between annual mean global temperatures and September sea ice extent holds even as the CO_2 forcing decreases. However, the linearity breaks down for the relationship between September sea ice and atmospheric CO_2 concentrations or cumulative CO_2 emissions once the CO_2 forcing decreases or stabilizes. This is due to the equilibration to the forcing once the transient increase stops or is reversed, in agreement with previous stabilization experiments[5]. Therefore, in order to return the sea ice extent to present day levels, cumulative CO_2 emissions and atmospheric CO_2 concentrations would need to be reduced below present-day levels to account for the equilibration of the climate to the forcing.

Overall, this study shows that limiting warming to 1.5 °C rather than 2.0 °C or more can greatly reduce the probability of sea ice extents below the minimum observed so far, the probability of seeing any ice-free conditions in the Arctic by 2100, the probability of ice-free conditions in a given year, the probability of consecutive ice-free Septembers, the probability of ice-free conditions occurring in months beside September, and the probability of an early ice-free September.

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Author contributions

A.J. designed the study, performed the analysis, and wrote the manuscript.

Competing financial interests

The author declares no competing financial interests.

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Methods

Simulations

To reliably assess the future sea ice state in the Arctic, we need ensemble simulations to quantify the impact of internal variability, which has been shown to be particularly large for Arctic summer sea ice[36,37,38,39]. Here we use five sets of CESM ensemble simulations to assess the likely state of the Arctic sea ice under RCP8.5 (40 members[21]), RCP4.5 (15 members[22]), and in scenarios that limit global warming to 1.5 °C, 1.5 °C with a temporary overshoot above 1.5 °C but reaching 1.5 °C by 2100, and 2.0 °C (10, 5, 10 members, respectively[20]). The CO_2 emissions per year, cumulative CO_2 emissions, and atmospheric CO_2 concentration used as forcing, as well as the resulting global temperature anomaly relative to pre-industrial (1850–1920) and the September sea ice extent in all of these simulations is shown in Fig. S.1.

These CESM ensemble simulations allow us to assess the impact of scenario versus internal variability uncertainty, but do not account for model structural uncertainty, as all simulations use the same model, the CESM1.1-CAM5. This version of the CESM has been widely used for Arctic sea ice studies[29,18 38,40,41], and generally performs well. A quantification of the sea ice sensitivity in the CESM compared to observations and CMIP5 models and a discussion of the small mean September sea ice extent bias are provided below.

Sea ice sensitivity

An assessment of the sea ice loss for a certain degree of warming (Fig. S.2), called sea ice sensitivity[2], suggests that this version of the CESM has a low sensitivity to warming, in particular for trends longer than 30 years. This underestimation of sea ice sensitivity agrees with previous work that showed that most CMIP5 models only simulate a sea ice loss as large as observed or larger for a greater warming than observed[23]. However, due to the large internal variability that impacts even the sea ice sensitivity obtained from 35 year trends (Fig. S.2f), some of the members of the CESM ensemble show sea ice sensitivities that overlap with some of the observational estimates (Fig. S.2f). The CESM sea ice sensitivity calculated over 1979–2016 ranges between -1.3 and -5.4 million km^2 per 1 °C warming. This range encompasses the observational sea ice sensitivity using the NSIDC sea ice extent[30] and the GISSTEMP[42,43] temperature (-4.2 to -4.8) and partially overlaps with the range obtained using the HadCRUT4.5[44,45] temperatures (-5.1 to -5.6). However, the CESM shows only minimal overlap with the sea ice sensitivity obtained using the NCDC[46,47] temperatures (-5.3 to -6.1). It is noteworthy that the NCDC based sensitivity also shows no overlap with the GISSTEMP based sensitivity, even though both represent the observed temperature anomaly over the same period (Fig. S.2f).

Compared to the suite of CMIP5 models, the CESM ensemble mean sea ice sensitivity of -2.94 km^2 per 1 °C is higher than the CMIP5 ensemble mean of -2.3 ± 0.6 km^2 per 1 °C [6] and is shifted closer to the observational estimates (Fig. S.2f). In fact, the large CESM LE ensemble spread suggests that the sea ice sensitivity from the CMIP5 models is likely strongly influenced by internal variability, and not just model differences (Fig. S.2f). It also shows that the standard deviation of the ensemble spread (0.8 million km^2 per 1 °C) does not capture the full range of internal variability (4.1 million km^2 per 1 °C, which is more than 2.5 times the standard deviation of the CESM LE, even when calculated from 35 year trends). So while the linear relationship between global temperature and September sea ice extent is very robust and is found in both observations and models[2,3,6,7], its exact slope is still influenced by internal variability on the timescales for which we have reliable sea ice observations. That means that we have to be extremely careful to compare a single model simulation with observations, as we can not know where in the distribution created by internal variability an individual simulation lies[39]. We also do not know where the observations lie within the spectrum of possible realizations of the real world. Using large ensembles, we can obtain the probability distribution due to internal variability within the model, and assess whether that range encompass the observations or not. That allows us to at least establish whether the model is consistent with the observations or not. But we are still left with a single realization of reality to compare with a distribution of many possible realizations from the model. Given that the CESM sea ice sensitivity is consistent with the one computed using GISSTEMP, but only overlaps with the low end of the HadCRUT4.5 and NCDC ones, a reasonable assessment is that the CESM sea ice sensitivity is likely low but can not be classified as biased since we do not know which temperature data samples the real world best. Nor do we know where in the probability space the real world temperature change is found.

A different but related measure of the sea ice sensitivity is the relationship between sea ice area and cumulative CO_2 emissions[10]. Internal variability again has a big impact on this metric, with a CESM ensemble range of -2.0 to -3.1 m^2/ton CO_2. As for the sea ice sensitivity, this range includes the observations (-3.0 m^2/ton CO_2) at the low end of the ensemble spread. Compared to the CMIP5 ensemble mean of -1.75 ± 0.67 m^2[10], the CESM LE ensemble mean of -2.5 m^2/ton CO_2 is higher and in better agreement with observations (Fig. S.2g).

Overall, we find that the observations fall at least partially within the CESM ensemble spread of sea ice sensitivity metrics (depending on the temperature data used), making the CESM consistent with some of the observationally-based emergent constraints. However, the observations are all found on the more sensitive edge of the CESM distribution. This suggests that the presented probabilities based on the CESM should be taken as a reasonable but likely conservative estimate.

Sea ice extent mean bias

In contrast to the sea ice sensitivity, we can see a clear positive bias in the CESM mean 1979–2016 September sea ice extent (Fig. S.2e), as the NSIDC[30] mean ice extent for the same periods is outside the ensemble spread from the CESM, by -0.23 million km^2. As that might impact the probabilities of September ice extents and ice-free conditions, it is worth investigating the effect of such a bias. However, this is not simple. First of all, the 1979–2016 averages in the CESM show a large impact of internal variability, and we do not know where in the probability distribution the real world sample lies. Second of all, we do not know whether this shift compared to observations is constant in time. Furthermore, as shown in Fig. S.5, the internal variability changes as a function of the sea ice extent. In order to provide a first-order assessment of the impact of this bias on the results presented, we assume that the mean bias stays the same into the future. Since we do not know where in the probability space the observational 1979–2016 average is located, we assume it is found in the part of the distribution from the CESM that is most likely. This means we shift all sea ice extents by -0.35 million km^2 (light blue histogram in Fig. S.2e). The effect of this shift on the calculated percentages is shown in Fig. S.3. This clearly shows that while such a shift affects the values of all probabilities, the general qualitative results stay the same. In particular, we still find a big difference between limiting warming to 1.5 °C versus 2.0 °C. The largest change occurs for the probability of one occurrence of ice-free conditions in September, which increases from 30% to 90% even if warming is limited to 1.5 °C. However, that only further enhances the contrast to the previous work by Screen and Williamson [19], since they found a 0% probability of ice-free conditions if warming is limited to 1.5 °C.

Data availability

All underlying data used in this study is freely available. The CESM ensemble model output used is freely available on the NCAR earth system gateway (www.earthsystemgrid.org). The observed temperature anomalies are available on the internet (data.giss.nasa.gov/gistemp/, www.metoffice.gov.uk/hadobs/hadcrut4/data/current/download.html, www.ncdc.noaa.gov/cag/time-series). NSIDC sea ice extent is available from the NSIDC website (https://nsidc.org/). The CMIP5 sea ice and temperature data is available in the CMIP5 archive (https://esgf-node.llnl.gov/projects/esgf-llnl/). The observed and CMIP5 sea ice sensitivity to cumulative CO_2 emissions is available in a table in Notz and Stroeve [10].

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Supplementary material

Reduced probability of ice-free summers for 1.5 °C compared to 2.0 °C warming

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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[?], 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.

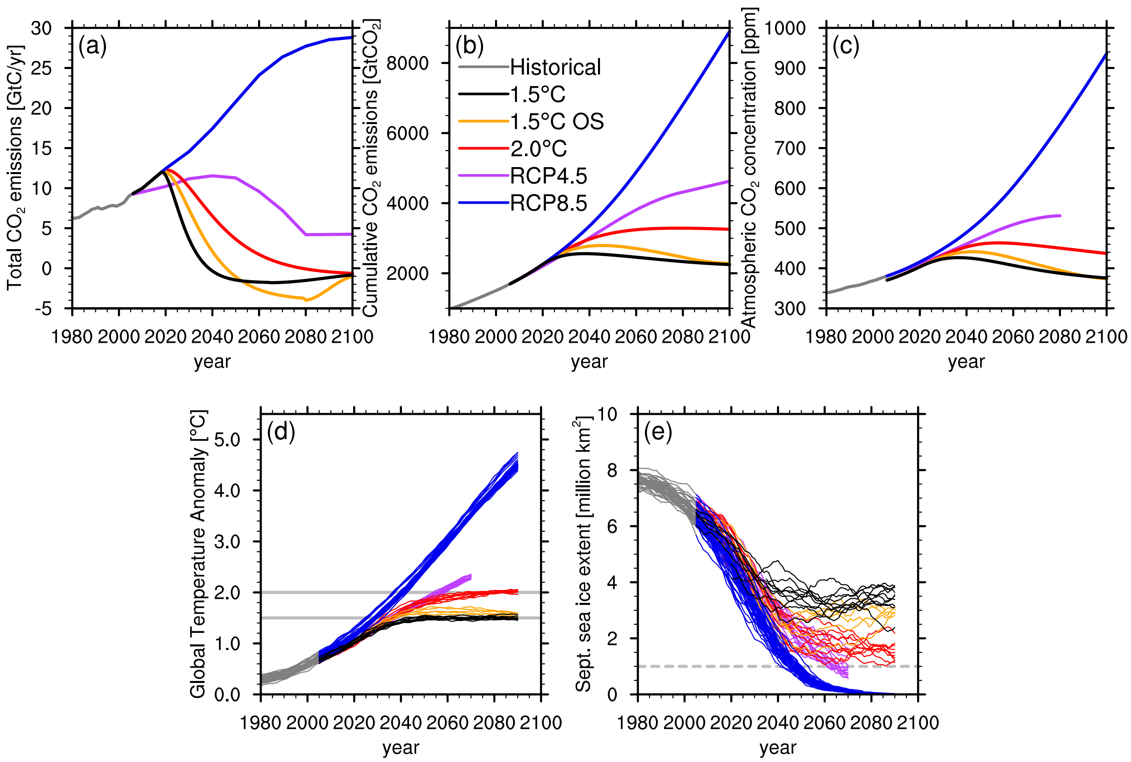

Figure S.1: **Forcing and climate response**: This figure shows (a) the total CO_2 emissions per scenario [in GtC/yr], (b) the resulting cumulative CO_2 emissions since 1850 [in $GtCO_2$], (c) the CO_2 forcing applied in the model [in ppm], (d) the resulting 20-yr running mean annual-mean global temperature 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).

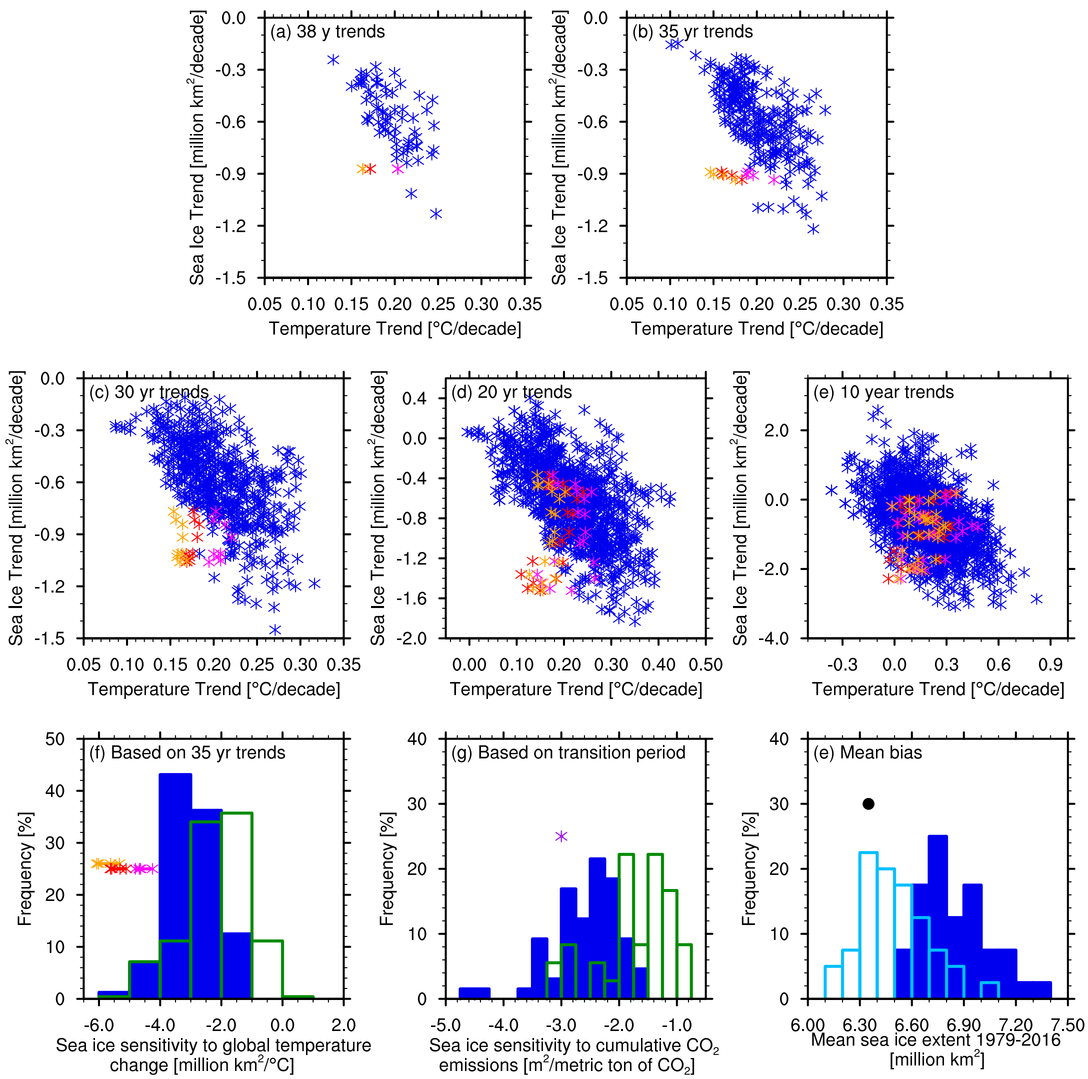

Figure S.2: **Assessment of CESM sea ice simulation:** Sea ice extent trends per decade versus global temperature trends per decade for various trend lengths (a-e) sampled from 1979–2016, in models and observational datasets. The CESM LE is shown in blue. Observational sea ice extent is from the NSIDC[?] and the global surface temperature is the HadCRUT4.5 data[? ?] (red), the GISS data[? ?] (magenta), and the NCDC temperature[? ?] (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[? ? ?]. Histograms for the CESM LE (blue) and the CMIP5 models (green)[?] 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[?] and the CMIP5 distribution from **?** in green. It also shows the single observational estimate from **?** 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[?] 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

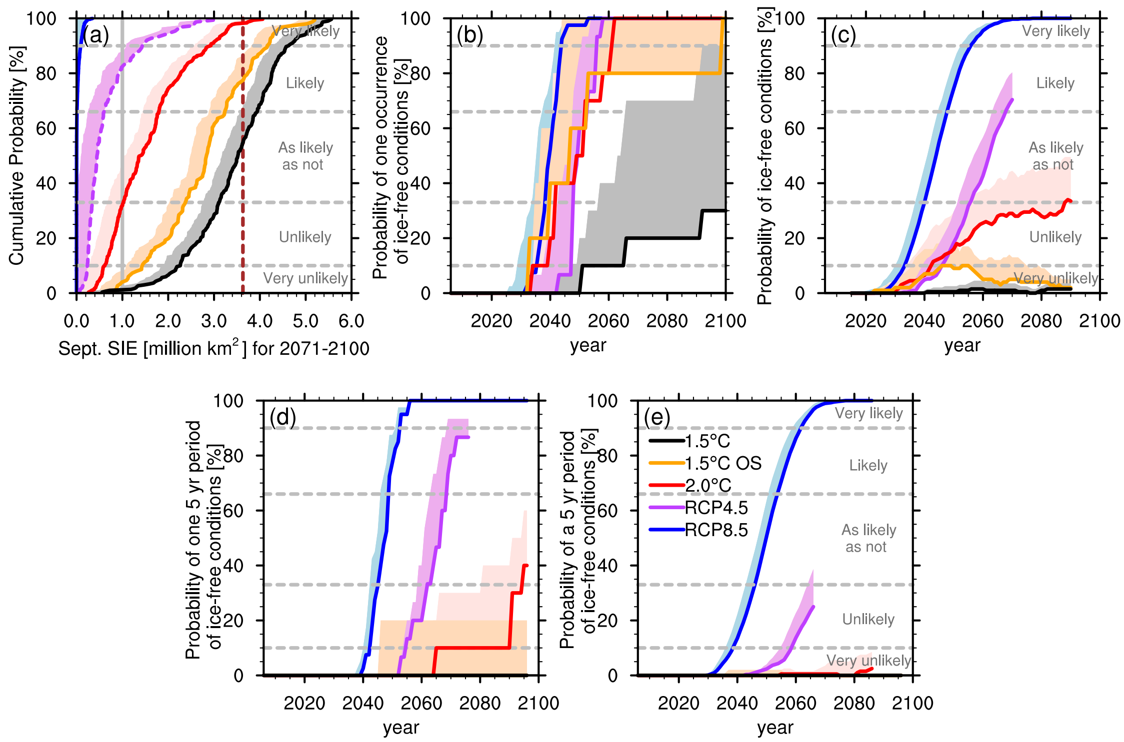

Figure S.3: **Additional probabilities:**(a-c) the solid lines show the same probabilities as shown in Fig. 1, but now with additional shading indicating the possible uncertainty of these probabilities due to CESM September mean being biased high over 1979–2016 (RCP8.5 in blue, RCP4.5 in purple, 2.0 °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).

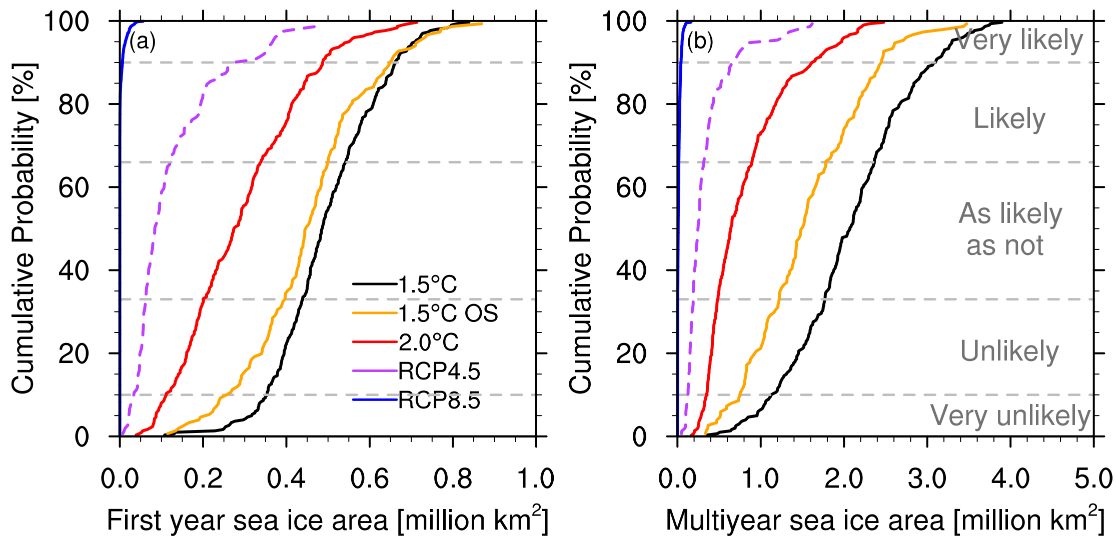

Figure S.4: **First year and multi-year sea ice:** Probabilities of (a) first-year and (b) multi-year sea ice area in the Arctic to be below a given value for different scenarios, for 2071–2100. Different scenarios are shown in different colors (RCP8.5 in blue, RCP4.5 in purple, 2.0 °C in red, 1.5 °C 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.

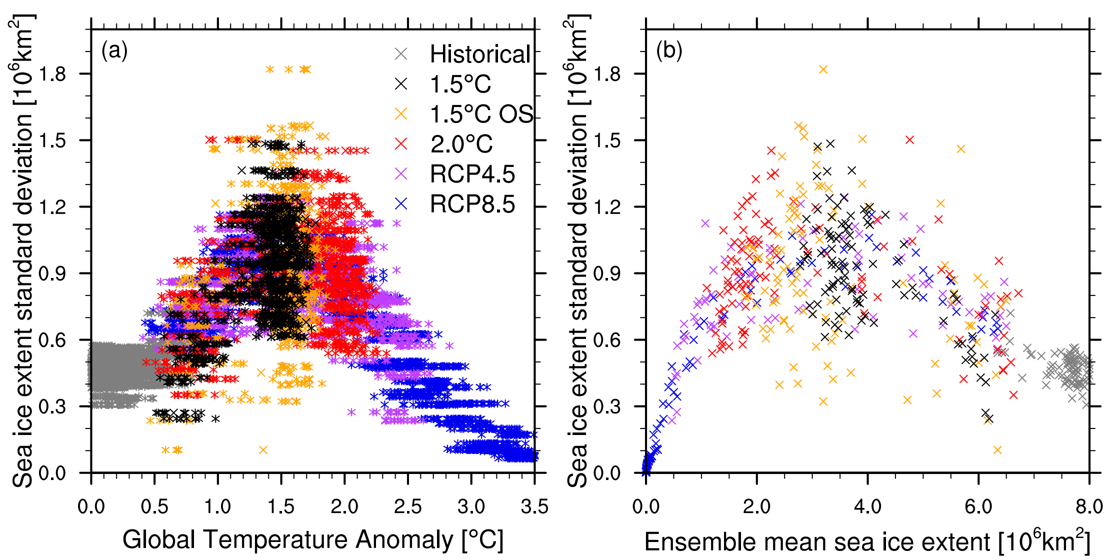

Figure S.5: **Change in the standard deviation of September sea ice extent** as function of (a) global mean temperature anomaly (relative to pre-industrial, 1850-1920) and (b) ensemble mean sea ice extent for all CESM ensembles from the different scenarios (color coded with RCP8.5 in blue, RCP4.5 in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