



**Abstract**

State-of-the-art climate models simulate a large spread in the projected decline of Arctic sea-ice area (SIA) over the 21st century. Here we diagnose causes of this intermodel spread using a model that approximates future SIA based on present SIA and the sensitivity of SIA to Arctic temperatures. This model accounts for 70–95% of the intermodel variance, with the majority of the spread arising from present-day biases. The remaining spread arises from model differences in Arctic warming, with some contribution from the local sea-ice sensitivity. Using observations to constrain the projections moves the probability of an ice-free Arctic forward by 10–35 years. Under a high-emissions scenario, an ice-free Arctic will likely (>66% probability) occur in September around 2046 and from July–October around 2059. Under a medium-emissions scenario, this date occurs around 2051 in September and 2080 from July–October. These observation-based constraints imply ice-free Arctic summers are approaching faster than previously thought.

**Plain Language Summary**

Arctic sea ice coverage has declined substantially over the past few decades and is projected to continue to decline over the next century. These projections, however, are marred by large uncertainties which arise primarily due to differences between climate models. In this study, we use a simple model that emulates the future evolution of Arctic sea ice as simulated by climate models to explain where this uncertainty comes from. We show that biases in simulating present-day Arctic sea ice contributes most of the uncertainty, with model differences in the simulated amount of Arctic warming contributing much of the rest. We then use observations to constrain our simple model and show that under a high emissions scenario it is likely the Arctic will be free of sea ice in September around 2046 and from July to October around 2059. We also show that the emissions pathway impacts the length of ice free summers in the Arctic. Nonetheless, these results imply ice free summers in the Arctic are approaching faster than previously thought.

## 1 Introduction

The rapid loss of Arctic sea ice over the last several decades has been one of the clearest manifestations of climate change. Since the beginning of the satellite record, Arctic sea ice has thinned substantially across all seasons, and its summertime coverage has declined by approximately 50% (Fetterer et al., 2016; Stroeve & Notz, 2018). Because sea ice plays an important role in shaping local ecosystems (Wyllie-Echeverria & Wooster, 1998; Laidre et al., 2008), the life of indigenous populations (Ford & Smit, 2004), and socioeconomic activities in the Arctic (Melia et al., 2016), there has been a concerted effort to determine when the Arctic will become seasonally ice free.

Estimates suggest that in September the Arctic will most likely be ice free ( $< 1$  million  $\text{km}^2$ ) by the end of the 21st century (Boé et al., 2009; Notz, 2015; Jahn, 2018; Niederdrenk & Notz, 2018; Sigmond et al., 2018). But it could be ice free as early as mid-century (Holland et al., 2006; Liu et al., 2013; Notz, 2015; Jahn, 2018; Notz & SIMIP Community, 2020; Diebold & Rudebusch, 2021) or in the 2030s (Wang & Overland, 2009; Overland & Wang, 2013; Snape & Forster, 2014; Diebold & Rudebusch, 2021). The large uncertainties in projections of Arctic sea-ice area (SIA) and the date of an ice-free Arctic arise primarily because of structural differences between state-of-the-art global climate models (GCMs) and how they respond to external forcing (Stroeve et al., 2012; Massonnet et al., 2012; Notz & SIMIP Community, 2020; Bonan et al., 2021). Emergent constraints, which rely on statistical relationships between observable aspects of the current climate system and future climate change across GCMs, have been used to reduce this spread (Boé et al., 2009; Massonnet et al., 2012; Hall et al., 2019; Senftleben et al., 2020). They suggest that the Arctic may experience ice free conditions in September at some point between 2045 and 2060. Yet, the factors underpinning some of the proposed emergent constraints are currently poorly understood (Hall et al., 2019); in particular, there has been no satisfactory accounting of the relative importance of the sea ice response to warming versus biases in simulating present-day sea ice.

One conceptually convenient metric to understand Arctic sea-ice changes is the sea ice sensitivity, defined as a change of SIA per degree of global warming (Winton, 2011) or per change in cumulative carbon-dioxide emissions (Notz & Marotzke, 2012; Notz & Stroeve, 2016). Because Arctic SIA has been found to be approximately linearly related to global-mean surface temperatures in individual GCMs (Gregory et al., 2002; Winton, 2011;

74 Armour et al., 2011; Mahlstein & Knutti, 2012; Rosenblum & Eisenman, 2017), it implies  
 75 that long-term variations in simulated global warming should be proportional to long-term  
 76 variations in simulated sea ice retreat, which is indeed seen in GCMs (Mahlstein & Knutti,  
 77 2012; Rosenblum & Eisenman, 2016, 2017; Jahn, 2018). This suggests that Arctic SIA at  
 78 some point in time  $A(t)$  can be approximated by

$$A(t) = \bar{A}_c + \gamma \cdot (T(t) - \bar{T}_c) \quad (1)$$

79 where  $\bar{A}_c$  is the climatological SIA in a specific reference period,  $\gamma$  is the sea ice sensitivity,  
 80 and  $T(t) - \bar{T}_c$  is the amount of warming relative to the climatological temperature  $\bar{T}_c$  in the  
 81 reference period. The sea ice sensitivity  $\gamma$  can be obtained from the observational record via  
 82 regression analysis (e.g., Niederdrenk & Notz, 2018). GCMs suggest, at least for annual-  
 83 mean data, that  $\gamma$  is fairly constant in time (Winton, 2011; Mahlstein & Knutti, 2012),  
 84 implying that the observational record can be used to estimate the true sea ice sensitivity.  
 85 However, because SIA relates more directly to Arctic warming than to global warming  
 86 (Olonscheck et al., 2019), we go a step further and interpret  $T(t) - \bar{T}_c$  as Arctic (60°N–  
 87 90°N) temperature changes instead of as global temperature changes. We therefore interpret  
 88  $\gamma$  as the *local* sea ice sensitivity, defined as a change of SIA per degree of Arctic warming.  
 89 Variations in annual Arctic SIA from 1979–2020 are well approximated by this expression  
 90 given observed Arctic surface temperature variations and an estimated (total least squares  
 91 regression) local sea ice sensitivity  $\gamma = -0.79 \times 10^6 \text{ km}^2 \text{ }^\circ\text{C}^{-1}$  (Fig. 1a). The expression  
 92 accounts for not only the long-term trend and year-to-year variations ( $r = 0.96$ ), but also  
 93 the detrended variability ( $r = 0.81$ ), which is thought to be crucial for determining when  
 94 the Arctic will be ice free (Jahn et al., 2016; Screen & Deser, 2019). From 1979–2020, Eq.  
 95 (1) with monthly estimates of  $\gamma$  also accounts for variations in SIA at monthly timescales,  
 96 capturing the large downward trend of Arctic SIA in the summer, the more muted decline  
 97 in the winter, and the interannual variations of Arctic SIA across all months (Fig. 1c and  
 98 1d). However, on monthly timescales, it is less clear if the observed local sea ice sensitivity  
 99 remains constant in time (Mahlstein & Knutti, 2012).

100 That Eq. (1) captures the trend and variability of observed Arctic SIA over the past  
 101 few decades suggests that it could also be used to explain the behavior of coupled GCMs.  
 102 According to Eq. (1), the spread among GCMs could arise from differences in the mean-  
 103 state SIA of each GCM ( $\bar{A}_c$ ), in the sensitivity of sea ice to Arctic temperature changes ( $\gamma$ ),  
 104 or in the amount of Arctic warming  $T(t) - \bar{T}_c$ . What can we make of the intermodel spread  
 105 in projections of Arctic SIA, and how does each term contribute to the total uncertainty?

106 If, for instance, mean-state biases were reduced across GCMs, how much more certain is  
107 the date of an ice-free Arctic? To address these questions, we use Eq. (1) to introduce a  
108 simple framework for partitioning model uncertainty in 21st century projections of Arctic  
109 SIA into contributions from these different factors. We then use observations to constrain  
110 the individual factors, which facilitates conclusions regarding the probability of seeing an  
111 ice-free Arctic in the coming decades.

## 112 **2 Sources of uncertainty in model projections of Arctic sea ice**

113 We first apply Eq. (1) to simulations in Phase 6 of the Coupled Model Intercomparison  
114 Project (CMIP6) (Eyring et al., 2016) with Historical and SSP5-8.5 forcing (details in  
115 Methods). Over all months, the proportion of variance across the GCMs that Eq. (1)  
116 accounts for varies between 70% and 95% during 2020–2100 (Fig. 2a). The period in which  
117 Eq. (1) accounts for the lowest fraction of intermodel variance occurs in early summer  
118 during the beginning of the 21st century, when approximately 70–80% of the intermodel  
119 variance is captured. Eq. (1) accounts for the most (>90%) intermodel variance in late fall  
120 and early winter, likely because model-to-model variations in climatological Arctic SIA are  
121 largest in the wintertime (Davy & Outten, 2020; Shu et al., 2020). Arctic SIA calculated  
122 from Eq. (1) also bears a striking similarity to the trajectory of each individual GCM for  
123 the summer months (Supplemental Figure S1), which is the primary season of interest in  
124 this study.

125 The ability of Eq. (1) to capture most of the intermodel variance suggests the three  
126 terms in Eq. (1) can be used to identify sources of intermodel spread in projections of  
127 Arctic SIA. Isolating the intermodel spread of each term (details in Methods) shows that  
128 in the near future, biases in present-day SIA ( $\bar{A}_c$ ) account for approximately 70–80% of  
129 the total intermodel variance (Fig. 2b). In winter, the effect of mean-state biases persists  
130 much longer into the 21st century than in the summer, largely because sea ice remains  
131 present, whereas summer sea ice disappears in most GCMs by 2065. In summer, mean-state  
132 biases are important initially, accounting for 40–50% of the intermodel spread for the first  
133 decade beyond 2020, but their contribution quickly diminishes to approximately 20–30% by  
134 2050. The remaining intermodel spread arises from differences in local sea ice sensitivities  
135 (Fig. 2c) and Arctic warming (Fig. 2d). In late fall, model differences in the local sea ice  
136 sensitivity account for approximately 30% of the intermodel variance at the end of the 21st  
137 century. Notably, at the summer minimum, the spread in local sea ice sensitivity explains

138 little intermodel variance at the end of the 21st century. The majority of the intermodel  
 139 spread in September Arctic SIA projections at the end of the 21st century is associated  
 140 with differences in Arctic warming simulated by GCMs, which accounts for over 80% of the  
 141 intermodel variance. In winter, variations in Arctic warming begin to matter toward the end  
 142 of the 21st century and make up approximately 30–40% of the total intermodel variance.  
 143 Similar results are found for a medium emissions scenario (SSP2-4.5) and a low-emissions  
 144 scenario (SSP1-2.6), though the relative role of intermodel differences in Arctic warming  
 145 decreases and accounts for 40–60% of the total summer variance by the end of the 21st  
 146 century (Supplemental Figure S2–S3).

### 147 **3 Constraining model projections of Arctic sea ice**

148 We can use Eq. (1) in conjunction with observations to constrain the intermodel spread  
 149 in projections of Arctic SIA. Satellites have been reliably monitoring Arctic sea ice concen-  
 150 tration since 1979, giving estimates of Arctic SIA for more than 40 years. Reanalysis datasets  
 151 similarly give relatively accurate estimates of Arctic temperatures going back to the early  
 152 1950s, when the U.S. Navy and other national meteorological institutes began regular, year-  
 153 round monitoring of the Arctic. We quantify how these observations constrain projections of  
 154 an ice-free Arctic (defined as the first year when each GCM crosses the 1 million<sup>2</sup> km<sup>2</sup> SIA  
 155 threshold) by fitting a Gaussian distribution to the GCM ensemble (details in Methods).  
 156 This is analogous to the cumulative frequencies of GCMs being ice-free.

#### 157 **3.1 September**

158 We begin by focusing on September Arctic SIA projections in GCMs, based on Eq.  
 159 (1), without observational constraints. Under a high-emissions scenario (SSP5-8.5), CMIP6  
 160 GCM estimates for the terms on the right-hand side of Eq. (1) suggest that it is ‘likely’  
 161 (>66% probability) the Arctic will experience an ice-free September by 2057 and that it  
 162 is ‘very likely’ (>90% probability) the Arctic will experience an ice-free September around  
 163 2100 (Fig. 3a). Raw GCM output predicts that these ice-free dates will occur 3-5 years  
 164 earlier than Eq. (1) (Supplemental Figure S4), implying that Eq. (1) provides a relatively  
 165 accurate estimate of the simulated behavior.

166 Correcting for mean-state biases in GCMs by using Eq. (1) with the mean-state of  
 167 September Arctic SIA from 1979–2020 in observations rather than GCMs, brings forward

168 the ‘likely’ date by 4 years to 2053 and brings forward the ‘very likely’ by 30 years (Figure  
169 3a). Note, this mean-state adjustment reduces the likelihood of seeing ice-free conditions  
170 in the next few decades. Next, using the observed local sea ice sensitivity  $\gamma$ , rather than  
171 that from each GCM in addition to the mean-state correction, moves the ‘likely’ date of an  
172 ice-free Arctic forward by three more years to 2050. The ‘very likely’ date moves forward  
173 by an additional 6 years to 2060. This indicates that GCMs tend to underestimate the  
174 observed local sea ice sensitivity in September.

175 The monthly local sea ice sensitivity is not constant in time in the GCM simulations;  
176 they systematically show increasingly negative values in the future. The more negative  $\gamma$   
177 values could arise from the fact that the relationship between sea ice thickness and area  
178 is not perfectly linear. At higher thickness regimes, a change in Arctic temperature would  
179 result in a smaller area change, whereas at lower thickness regimes, the same change in  
180 Arctic temperature would result in a larger area change. Estimating  $\gamma$  from 1979 up until  
181 a particular year yields an estimate of how the local sea ice sensitivity evolves in the future  
182 according to state-of-the-art GCMs (see Methods). With this added guidance, the ‘likely’  
183 date of seeing an ice-free Arctic in September moves forward by 4 years to 2046. This  
184 constraint moves forward the ‘very likely’ date of ice free conditions in September by 5  
185 years to 2055, which is close to 50 years sooner than the CMIP6 GCMs suggest. Internal  
186 variability, which can be estimated from a single-model initial condition large ensemble,  
187 adds uncertainty to the ice-free date (Jahn et al., 2016; Screen & Deser, 2019; Bonan et al.,  
188 2021) and implies an error range of approximately  $\pm 8$  years on these estimates. That is,  
189 under a high-emissions scenario, our constraint suggests that an ice-free September in the  
190 Arctic is ‘likely’ to occur between 2038–2053 and ‘very likely’ to occur between 2047–2063.

191 The same observational constraints can be applied under medium- and low-emissions  
192 scenarios. CMIP6 GCMs in conjunction with Eq. (1) suggest the ‘likely’ date of an ice-  
193 free Arctic in September occurs in 2064 and 2100 for medium- and low-emissions scenarios,  
194 respectively (Fig. 3b-c). Applying the same observational constraints on  $\bar{A}_c$  and  $\gamma$  shifts  
195 this date to 2051 and 2091 for medium- and low-emissions scenarios, respectively. In both  
196 the medium- and low-emissions scenarios, correcting for mean-state biases pushes back the  
197 date of an ice-free Arctic. The observed local sea ice sensitivity moves forward the date  
198 of ice-free conditions for the medium-emissions scenario, but it does relatively little to the  
199 low-emission scenario. In both scenarios, the future evolution of the local sea ice sensitivity  
200 (diagnosed separately for each emissions scenario) moves forward the date of an ice-free

201 Arctic. When compared to the CMIP6 output, the constraints shift the ‘as likely as not’  
202 (>33% probability) date for the medium-emissions scenario forward by approximately 7  
203 years and the ‘likely’ date forward by approximately 15 years (Fig. 3b).

### 204 **3.2 Late summer and early fall**

205 Seasonality of an ice-free Arctic (Jahn, 2018; Niederdrenk & Notz, 2018; Årthun et  
206 al., 2021) is a feature of Arctic SIA projections that remains less quantified. Under a high  
207 emissions scenario, CMIP6 GCMs suggest that by 2081 the Arctic will ‘likely’ experience  
208 ice free conditions in July (Fig. 4a). Applying the same constraints on  $\bar{A}_c$  and  $\gamma$  for July  
209 suggests the ‘likely’ date of an ice-free July is actually 2051, approximately 30 years sooner  
210 than GCMs suggest. This is related to the fact that GCMs have large biases in  $\bar{A}_c$  and  $\gamma$  in  
211 July when compared to observations. Internal variability changes this estimate to between  
212 2044 and 2058. For August, a similar picture emerges. CMIP6 GCMs suggest the Arctic  
213 will ‘likely’ experience ice free conditions in August by 2058, but the constrained estimate  
214 is 2048 with a range of 2043 and 2053 due to internal variability (Fig. 4b). The ‘very likely’  
215 year is around 2056. All of these estimates are 10–30 years sooner than the GCMs suggest  
216 and the ‘very likely’ date moves forward by almost 50 years. October shows a similar picture  
217 to the other months. The ‘likely’ year of the Arctic experiencing ice-free conditions is 2070  
218 (Fig. 4d). Observational constraints of  $\bar{A}_c$  and  $\gamma$  moves forward this year to 2059, more  
219 than 10 years sooner than most GCMs suggest. The ‘very likely’ date is around 2071, which  
220 is approximately 30 years sooner than raw GCM projections.

221 Under SSP2-4.5 these constraints suggest the ‘likely’ date when the Arctic will experi-  
222 ence an ice-free July occurs around 2058 (Fig. 4a). For SSP1-2.6, by the end of the  
223 21st century it is ‘as likely as not’ that the Arctic will experience ice-free conditions in  
224 July. Furthermore, the probability of seeing ice-free conditions from July to October is  
225 greatly increased when compared to the raw output and will ‘likely’ occur around 2080 for  
226 a medium-emissions scenario. For a low-emissions scenario, at the end of the 21st century,  
227 the Arctic will ‘likely’ be ice free in September but not in other months. This suggests that  
228 the emissions scenario matters for the length of the ice-free season.

## 4 Discussion

While previous studies have also reduced the intermodel spread in Arctic SIA projections (Wang & Overland, 2009; Boé et al., 2009; Massonnet et al., 2012; Notz & SIMIP Community, 2020), most have done so by neglecting GCMs that poorly simulate present-day Arctic sea ice. The fact that GCMs can match observations for the wrong reasons (e.g., Rosenblum & Eisenman, 2017) suggests studies examining future projections should apply physically meaningful and robust constraints, rather than neglecting GCMs that do not meet certain observational criteria. This may explain why our results differ from the conclusions of Notz & SIMIP Community (2020), which find that after applying observational constraints even under a low-emissions scenario the majority of GCMs become ice-free by mid-century. Here, we find under a low-emissions scenario, the majority of GCMs instead become ice-free by 2082. These differences likely arise because we retain more intermodel differences in the simulated amount of Arctic warming.

This work, however, requires a few caveats. There are uncertainties associated with our observational estimates of Arctic warming and Arctic SIA that may change how well GCMs match observations, and change our observational estimates of  $\gamma$ , particularly at monthly timescales (Niederdrenk & Notz, 2018). We also did not explore the role of model inter-dependency (e.g., Sanderson et al., 2015; Knutti et al., 2017) on these conclusions. Investigation of how uncertainty in observations and model inter-dependency influence the results here should be the subject of future work.

## 5 Summary

This study introduces a simple framework to explain and constrain model projections of Arctic SIA over the 21st century. We find that a simple model (Eq. 1), which approximates future SIA based on present SIA and the sensitivity of SIA to Arctic temperatures, is able to emulate the evolution of Arctic SIA with remarkable skill. This model accounts for 70–95% of the intermodel variance in projections of Arctic SIA. Isolating the contributing factors shows that the majority of the model uncertainty in projections of Arctic SIA arises from biases in simulating present-day Arctic SIA. The remaining model uncertainty arises from differences in the simulated amount of Arctic warming, with some contribution from differences in the local sea ice sensitivity. While it is unclear whether Arctic temperatures are driving sea ice loss, or vice-versa, it does suggest that climate sensitivities (e.g., Meehl

260 et al., 2020) and representation of clouds in these GCMs (e.g., Zelinka et al., 2020) may be  
261 key to understanding the fate of Arctic sea ice.

262 Using observations to constrain the individual components of Eq. (1) moves forward the  
263 date of an ice free Arctic by 10–35 years. Under a high-emissions scenario, the probability  
264 of seeing ice-free conditions in the Arctic in September around 2035 is ‘as likely as not’,  
265 and the probability of seeing ice-free conditions in the Arctic in September around 2068 is  
266 ‘virtually certain’, which is much sooner than climate models suggest. The fate of Arctic  
267 sea ice throughout the summertime is similar. The probability of seeing ice-free conditions  
268 from July to October around 2059 is ‘likely’, and it is ‘very likely’ that the Arctic will  
269 experience ice-free conditions that persist from July to October around 2070 under a high-  
270 emissions scenario. Whereas previously it was widely believed that the Arctic will be ice  
271 free in September by mid-century under high emissions (Holland et al., 2006; Boé et al.,  
272 2009; Liu et al., 2013; Jahn, 2018; Niederdrenk & Notz, 2018; Sigmond et al., 2018; Notz &  
273 SIMIP Community, 2020), our work suggests that it is more likely that the Arctic will be ice  
274 free from July to October, not just in September. Importantly, by mid-century these dates  
275 shift under reduced emissions scenarios. Under a medium-emissions scenario, the Arctic  
276 will ‘likely’ only experience ice-free conditions from July to October after 2080. Under a  
277 low-emissions scenario, the Arctic will ‘likely’ only be ice free in September at the end of  
278 the 21st century. These results suggest the emissions scenario determines the length of the  
279 ice-free season. Overall, our results paint a dire picture of Arctic sea ice loss, implying  
280 ice-free summers in the Arctic are approaching faster than previously thought.

## 281 **6 Methods**

### 282 **6.1 Observations**

283 Monthly Arctic SIA from 1979 to 2020 was derived using observations of monthly sea  
284 ice concentration from the National Snow and Ice Data Center passive microwave retrievals  
285 bootstrap algorithm (Fetterer et al., 2016). For observation-based data of near-surface air  
286 temperature in the Arctic, we use the ERA5 global reanalysis (Hersbach et al., 2020). We  
287 use reanalysis data due to sparse data coverage of the Arctic toward the beginning of the  
288 satellite era. Monthly Arctic temperatures from 1979 to 2020 are obtained by calculating  
289 the average near-surface air temperature from 60°N to 90°N.

## 6.2 CMIP6 and large ensemble output

This analysis includes all CMIP6 GCMs (Eyring et al., 2016) that provide monthly output of sea ice concentration (‘siconc’) and near-surface air temperature (‘tas’) for Historical, SSP1-2.6, SSP2-4.5, and SSP5-8.5 simulations (29 different GCMs; see Supplementary Table 1). The Historical simulations (1850–2014) are merged with the SSP simulations (2015–2100). For each GCM, we use sea ice concentration to compute monthly Arctic SIA. Arctic temperatures are calculated as the average near-surface air temperature from 60°N to 90°N. We focus on single ensemble members from each GCM to mitigate over-weighting with respect to one GCM.

We also use the 40-member Community Earth System Model Large Ensemble (CESM1-LE) (Kay et al., 2015) to quantify how internal variability impacts estimates of when the Arctic first becomes seasonally ice free. The CESM1-LE uses RCP8.5 forcing, which differs slightly from the SSP5-8.5 forcing in the CMIP6 GCMs, but we expect the representation of internal variability under the RCP8.5 and SSP5-8.5 forcing to be similar. From each member we use sea ice concentration to compute monthly SIA and calculate Arctic-wide temperatures as the average near-surface air temperature from 60°N to 90°N.

## 6.3 Components of the simple model

Eq. (1) contains three components that are diagnosed from observations and the CMIP6 GCMs. The average Arctic SIA for a specific reference period  $\bar{A}_c$  is calculated as the time-mean Arctic SIA from 1979–2020 for each month in all GCMs and in observations. The local sea ice sensitivity  $\gamma$  is defined as the change of SIA per degree of Arctic (60°N–90°N) warming. This formulation enables us to capture inter-annual variability of SIA related to Arctic temperature variability that is not captured when using the global-mean (Winton, 2011) or Northern Hemisphere mean (Armour et al., 2011). For each month,  $\gamma$  is computed using total least squares regression from 1979–2020 in observations and 1979–2100 in the CMIP6 GCMs for all values of SIA above 1 million km<sup>2</sup> following, Winton, (2011). For Figure 1,  $\gamma$  is calculated from 1979–2020 for each month using the observed Arctic SIA and Arctic temperatures obtained from ERA5. For Figure 2,  $\gamma$  is calculated from the GCMs over the Historical and SSP5-8.5 period from 1979–2100. For Figures 3–4,  $\gamma$  is calculated from 1979–2100 to produce the black line. Given that GCMs show more negative values of  $\gamma$  in the future, we further approximate  $\gamma$  from 1979 to a particular year until the end of the

321 21st century to obtain the future evolution of  $\gamma$  in GCMs. Figure S6 shows how the local  
 322 sea ice sensitivity for each GCM evolves in time from 1979 up to the particular date for  
 323 the months of July, August, September, and October. This is used to produce the red line  
 324 in Figures 3 and 4 (which is further detailed below).  $\bar{T}_c$  is the average Arctic temperature  
 325 from 1979–2020 in each GCM and in observations, and  $T(t)$  is the Arctic temperature for a  
 326 given year and month.

#### 327 **6.4 Analysis of variance**

328 The ability of Eq. (1) to explain the intermodel spread in CMIP6 Arctic SIA projections  
 329 (Fig. 2a) is computed as the proportion of the variance ( $r^2$ , where  $r$  is the Pearson correlation  
 330 coefficient) in monthly Arctic SIA from CMIP6 GCMs that is explained by Eq. (1) as a  
 331 function of year and month. To examine the contribution of each term in Eq. (1) to  
 332 the intermodel spread of Arctic SIA projections (Fig. 2b-d), we use the propagation of  
 333 uncertainty to quantify the effect of uncertainty from each variable on the total uncertainty.  
 334 Specifically, we apply the full intermodel spread of one term and hold the other two terms at  
 335 their multi-model mean values yielding three sets of time series for  $A(t)$ , each containing 29  
 336 realizations, which are the result of the intermodel spread of each individual term. Assuming  
 337 linearity, the total variance for a given month  $m$  and year  $y$  is:

$$T(m, y) = M(m, y) + S(m, y) + W(m, y) \quad (2)$$

338 where the fractional uncertainty from a given source is calculated as  $M/T$ ,  $S/T$ , and  $W/T$ .  
 339  $M$  is calculated as the variance due to the intermodel spread in  $\bar{A}_c$ ,  $S$  is calculated as the  
 340 variance due to the intermodel spread in  $\gamma$ , and  $W$  is calculated as the variance due to  
 341 the intermodel spread in  $T(t) - \bar{T}_c$ . The covariance terms are small and vary between 5–  
 342 31%, which can be confirmed by calculating the residual between Fig. 2a and the variance  
 343 explained by the sum of the three individual terms.

#### 344 **6.5 Probability density functions**

345 The date of an ice-free Arctic is taken to be the first year when SIA falls below the  
 346 1 million km<sup>2</sup> threshold (Wang & Overland, 2009). This threshold, rather than zero, is  
 347 commonly used since some sea ice may remain along the northern coasts of Greenland  
 348 and Ellesmere Island after the bulk of the Arctic Ocean becomes open water. Assuming a

349 Gaussian distribution, the probability can be obtained as:

$$P(t_1 < t < t_2) = \int_{t_1}^{t_2} f(t)dt = \int_{t_1}^{t_2} \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(t-\mu)^2}{2\sigma^2}} dt \quad (3)$$

350 where  $\mu$  is the multi-model mean of the CMIP6 GCMs,  $\sigma$  is the standard deviation of  
 351 all CMIP6 GCMs, and  $t$  is the ice-free date. Because some GCMs do not project ice-free  
 352 conditions in the 21st century, each probability is normalized by the number of GCMs  
 353 used relative to the total number of GCMs, which makes this analogous to the cumulative  
 354 frequencies of GCMs being ice-free. In this paper, we adopt the IPCC likelihood scale  
 355 where ‘very unlikely’ means 0–10%, ‘unlikely’ means 0–33%, ‘as likely as not’ means 33–  
 356 66%, ‘likely’ means 66–100%, and ‘very likely’ means 90–100%. In Figures 3–4, the black  
 357 line is the cumulative probability density function using Eq. (1) and the raw CMIP6 output.  
 358 In Figure 3, the blue line is the cumulative density function after Eq. (1) is adjusted to  
 359 have  $\bar{A}_c$  be equal to the average September Arctic SIA from observations (1979–2020); the  
 360 purple line is the same formulation as the blue line, but also with the observed  $\gamma$  for each  
 361 month as estimated using the total least squares regression from observations (1979–2020);  
 362 and the red line is the same as the blue and purple line, except that it contains guidance  
 363 from the GCMs on how  $\gamma$  evolves in the future since for individual months it is not constant  
 364 in time (see Fig. S6). Here  $\gamma$  is estimated from total least squares regression from 1979 to a  
 365 particular date in each each month to obtain the future evolution of  $\gamma$  according to GCMs.  
 366 Normalizing the multi-model mean of these timeseries with observations by dividing by the  
 367 first value and multiplying by the observed value constrains the GCMs based on the observed  
 368 sensitivity and guides the equation how  $\gamma$  evolves into the future. The red shading in Figure  
 369 3 indicates the estimate of internal variability from CESM1-LE, which is calculated as the  
 370 two standard deviation of the CESM1-LE probability (see Fig. S5).

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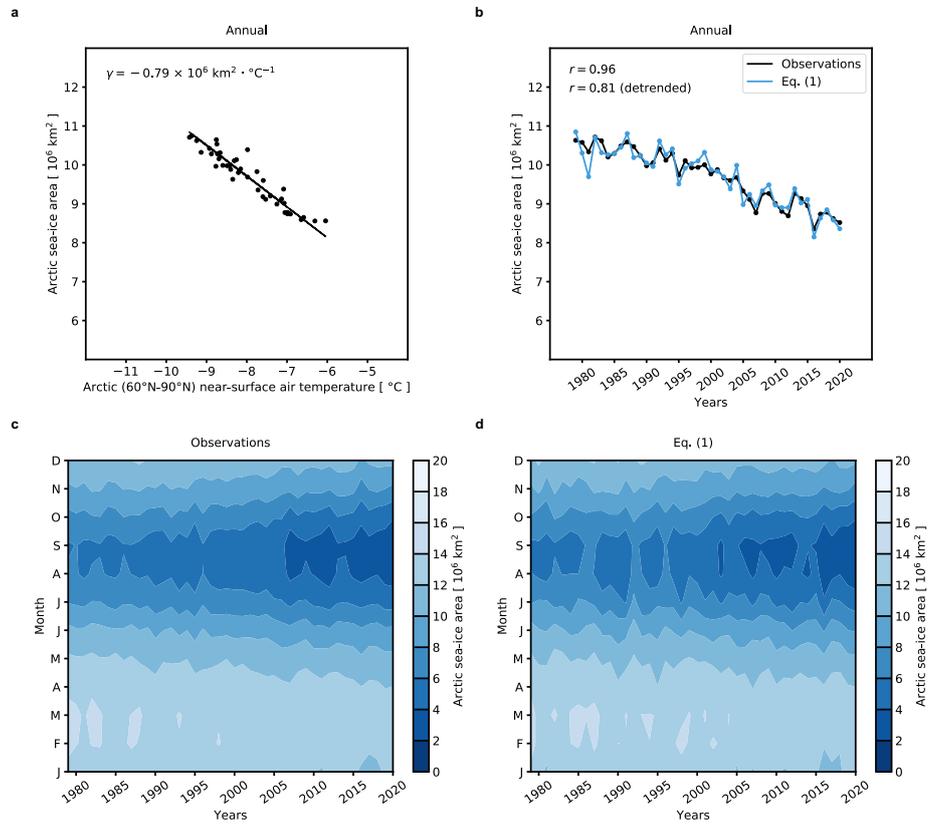
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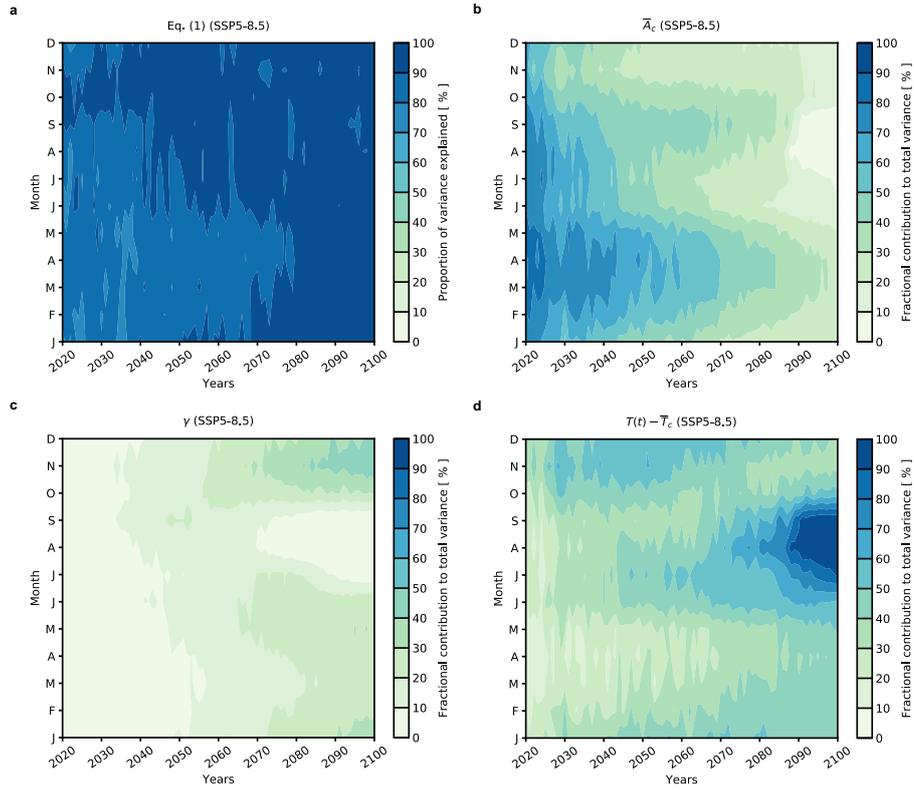
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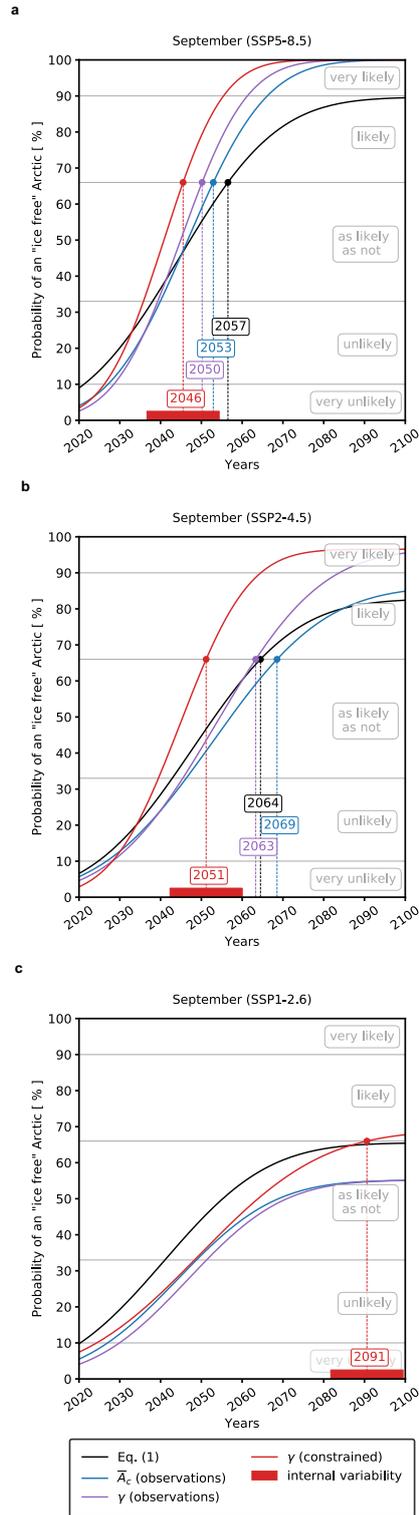
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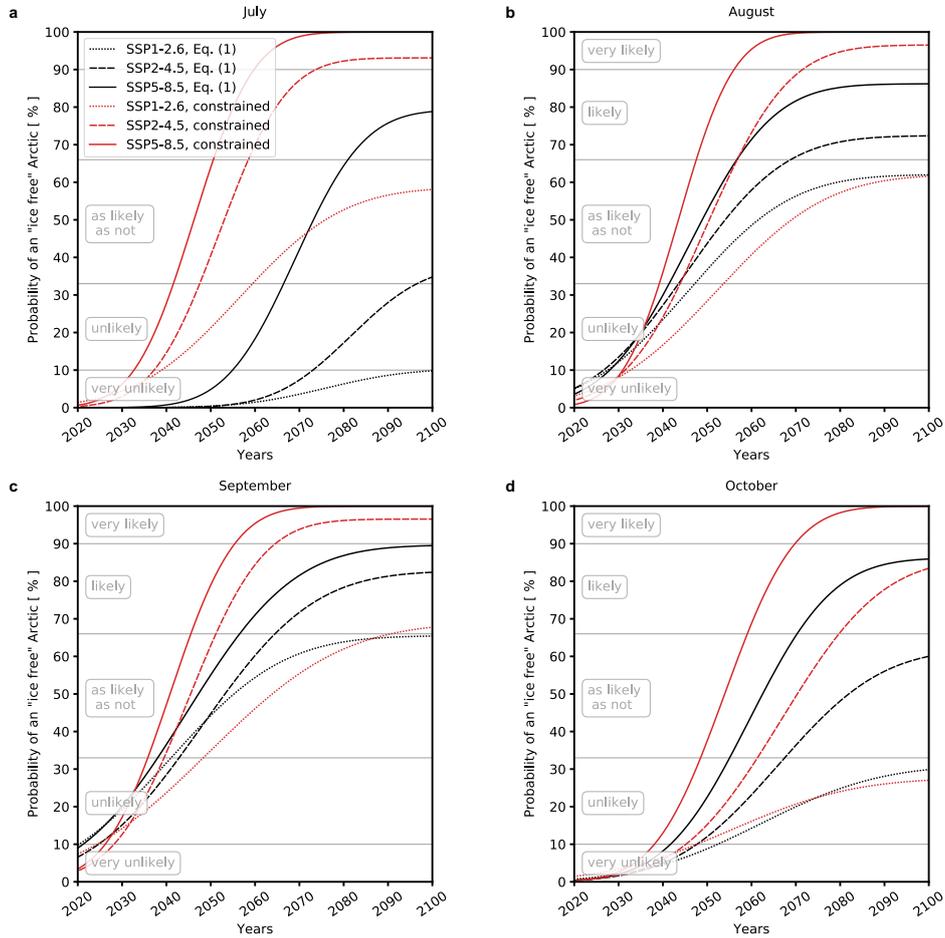
**Figure 1. Applying the simple model (Eq. 1) to observations.** (a) Scatter plot showing the relationship between observed annual Arctic (60°–90°N) near-surface air temperature and annual Arctic sea-ice area from 1979–2020, implying a local sea ice sensitivity of  $\gamma = -0.79 \times 10^6 \text{ km}^2 \cdot ^\circ\text{C}^{-1}$ . (b) Annual Arctic sea-ice area from 1979–2020 in observations (black) and using Eq. (1) with observed temperature variations (blue). The correlation between the two time series is shown in the upper left with and without the linear trend. Monthly Arctic sea-ice area from 1979–2020 in (c) observations and (d) using Eq. (1) with  $\gamma$  estimated for each month.



**Figure 2. Partitioning intermodel variance in projections of Arctic sea-ice area.** (a) The proportion of the intermodel variance ( $r^2$ , where  $r$  is the Pearson correlation coefficient) in monthly Arctic sea-ice area from CMIP6 SSP5-8.5 simulations that is accounted for by Eq. (1) as a function of month and year. Fractional contribution of (b)  $\bar{A}_c$ , (c)  $\gamma$ , and (d)  $T(t) - \bar{T}_c$  to the total variance for SSP5-8.5 as a function of month and year.



**Figure 3. Probability of an ice-free Arctic in September.** Cumulative probability density function for the year when the Arctic will experience ice free conditions in September for (a) SSP5-8.5, (b) SSP2-4.5, (c) SSP1-2.6. The black line is the unconstrained Eq. (1) using CMIP6. The blue line is constrained by the mean September Arctic sea-ice area from 1979–2020 in observations. The purple line is constrained by both the mean September Arctic sea-ice area and local sea ice sensitivity from 1979–2020 observations. The red line is the same as the purple line, but with guidance from the GCMs on how the local sea ice sensitivity evolves in the future. The red shading denotes the range due to internal variability estimated from the CESM1-LE.



**Figure 4. Probability of an ice-free Arctic from July to October.** Cumulative probability density function for the year when the Arctic will experience ice free conditions in (a) July, (b) August, (c) September, and (d) October. The black line is the unconstrained Eq. (1) using CMIP6. The red line is the constrained output with the observed  $\bar{A}_c$  and  $\gamma$ , and with guidance on how the local sea ice sensitivity evolves in the future (as in Figure 3). The solid lines, dashed lines, and dotted lines denote SSP5-8.5, SSP2-4.5, and SSP1-2.6, respectively.