

Constraining the date of a seasonally ice-free Arctic using a simple model

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Key Points:

- A model relating future SIA to present SIA and local sea-ice sensitivity is used to explain the intermodel spread in Arctic SIA projections
- Biases in simulating present-day SIA contribute most to the spread, with model differences in Arctic warming contributing the rest
- Under a high-emissions scenario, the Arctic will likely be ice-free in September between 2036–2056 and from July–October between 2050–2068

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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 simple 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 intermodel differences in Arctic warming, with some contribution from differences in the local sea-ice sensitivity. Using observations to constrain the projections moves the probability of an ice-free Arctic forward by 10–35 years when compared to unconstrained projections. Under a high-emissions scenario, an ice-free Arctic will likely (>66% probability) occur between 2036–2056 in September and 2050–2068 from July–October. Under a medium-emissions scenario, the ‘likely’ date occurs between 2040–2062 in September and much later in the 21st century from July–October.

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 contribute most of the uncertainty, with climate model differences in the simulated amount of Arctic warming contributing much of the rest. We 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 sometime between 2036–2056 and from July to October sometime between 2050–2068. We also show that the emissions pathway impacts the length of ice free summers in the Arctic, indicating a low-emissions pathway will reduce the likelihood of seeing ice-free Arctic summers.

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 the Arctic will most likely be ice free (< 1 million km²) in September 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; Årthun et al., 2021; 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, γ 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 γ 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 γ 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; Ding et al., 2019), we go a step further and interpret $T(t) - \bar{T}_c$
 87 as Arctic (60°N–90°N) temperature changes instead of as global temperature changes. We
 88 therefore interpret γ as the *local* sea ice sensitivity, defined as a change of SIA per degree
 89 of Arctic warming. Variations in annual Arctic SIA from 1979–2020 are well approximated
 90 by this expression given observed Arctic surface temperature variations and an estimated
 91 (total least squares regression) local sea ice sensitivity $\gamma = -0.80 \times 10^6 \text{ km}^2 \text{ }^\circ\text{C}^{-1}$ (Fig.
 92 1a). The expression accounts for not only the long-term trend and year-to-year variations
 93 ($r = 0.96$), but also the detrended variability ($r = 0.81$), which is thought to be crucial
 94 for determining when the Arctic will be ice free (Jahn et al., 2016; Screen & Deser, 2019).
 95 From 1979–2020, Eq. (1) with monthly estimates of γ also accounts for variations in SIA
 96 at monthly timescales, capturing the large downward trend of Arctic SIA in the summer,
 97 the more muted decline in the winter, and the interannual variations of Arctic SIA across
 98 all months (Fig. 1c and 1d). However, on monthly timescales, it is less clear if the observed
 99 local sea ice sensitivity 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 (γ),
 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? If,

106 for instance, mean-state biases were reduced across GCMs, how much would this reduce the
107 uncertainty in the date of an ice-free Arctic? Indeed, the mean SIA and the sensitivity of
108 sea ice to global temperature changes in each GCM have been shown to be well correlated
109 with the date of an ice-free Arctic (Massonnet et al., 2012; Jahn, 2018; Notz & SIMIP
110 Community, 2020). For example, Notz & Community, (2020) show that considering only
111 GCMs that correctly simulate both the mean September Arctic SIA and observed sensitivity
112 of September Arctic SIA to cumulative CO₂ emissions suggests the Arctic will be ice-free
113 in September before mid-century, regardless of the emissions scenario. However, previous
114 work has shown that GCMs can match observations for the wrong reasons (e.g., Rosenblum
115 & Eisenman, 2017), suggesting that including only GCMs that correctly simulate certain
116 observed criteria may impact estimates of when an ice-free Arctic will occur. Instead of
117 neglecting GCMs that do not meet certain observational criteria, future projections should
118 be constrained in a systematic manner that includes physically justifiable constraints.

119 To address these questions, we use Eq. (1) to introduce a simple framework for parti-
120 tioning model uncertainty in 21st century projections of Arctic SIA into contributions from
121 \bar{A}_c , γ , and $T(t) - \bar{T}_c$. This work builds on previous work (e.g., Mahlstein & Knutti, 2012;
122 Jahn, 2018; Notz & SIMIP Community, 2020) by constructing a simple model that further
123 exploits the linear relationship between Arctic SIA and Arctic temperatures and shows how
124 observations can be used to systematically reduce uncertainty in model projections of Arctic
125 sea ice. We then use observations to constrain the individual factors of our simple model,
126 which facilitates conclusions regarding the probability of seeing an ice-free Arctic in the
127 coming decades.

128 **2 Methods**

129 **2.1 Observations**

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

2.2 CMIP6 and large ensemble output

We analyze 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 use the 50-member Canadian Earth System Model Large Ensemble Version 5 (CanESM5-LE; Swart et al., 2019) to quantify how internal variability impacts estimates of when the Arctic first becomes seasonally ice free. The CanESM5-LE contains 50 ensemble members each for SSP1-2.6, SSP2-4.5, and SSP5-8.5 forcing, enabling us to estimate internal variability ranges unique to each forcing scenario. Internal variability has been shown to increase as forcing decreases (Jahn, 2018). From each member, we use sea ice concentration to compute monthly SIA.

2.3 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 \overline{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 γ 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, γ 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 km², following Winton, (2011). GCMs show more negative values of γ in the future; Figure S1 shows how the local sea ice sensitivity for each GCM evolves in time from 1979 up to the particular date for the months of July, August, September, and October, where γ is computed from 1979 to the date of interest. In order to constrain γ based on observations, we normalize the multi-model mean of these timeseries by dividing by the first value and multiplying by the observed value.

168 This constrains the GCMs based on the observed sensitivity and guides the equation how
 169 γ evolves into the future. Finally, \bar{T}_c is the average Arctic temperature from 1979–2020 in
 170 each GCM and in observations, and $T(t)$ is the Arctic temperature for a given year and
 171 month.

172 2.4 Analysis of variance

173 The ability of Eq. (1) to explain the intermodel spread in CMIP6 Arctic SIA projec-
 174 tions is computed as the proportion of the variance (r^2 , where r is the Pearson correlation
 175 coefficient) in monthly Arctic SIA from CMIP6 GCMs that is explained by Eq. (1) as a
 176 function of year and month. To examine the contribution of each term in Eq. (1) to the in-
 177 termodel spread of Arctic SIA projections, we use the propagation of uncertainty to quantify
 178 the effect of uncertainty from each variable on the total uncertainty. Specifically, we apply
 179 the full intermodel spread of one term and hold the other two terms at their multi-model
 180 mean values yielding three sets of time series for $A(t)$, each containing 29 realizations, which
 181 are the result of the intermodel spread of each individual term. Assuming linearity and that
 182 the factors are uncorrelated, the total variance for a given month m and year y is

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

183 where the fractional uncertainty from a given source is calculated as M/T , S/T , and W/T .
 184 M is calculated as the variance due to the intermodel spread in \bar{A}_c , S is calculated as the
 185 variance due to the intermodel spread in γ , and W is calculated as the variance due to
 186 the intermodel spread in $T(t) - \bar{T}_c$. The covariance terms are small and vary between 5–
 187 31%, which can be confirmed by calculating the residual between Fig. 2a and the variance
 188 explained by the sum of the three individual terms.

189 2.5 Probability density functions

190 The date of an ice-free Arctic is taken to be the first year when SIA falls below the
 191 1 million km² threshold (Wang & Overland, 2009). This threshold, rather than zero, is
 192 commonly used since some sea ice may remain along the northern coasts of Greenland and
 193 Ellesmere Island after the bulk of the Arctic Ocean becomes open water. The probability
 194 P can be obtained as

$$P(t) = \int_{t_0}^t \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(t-\mu)^2}{2\sigma^2}} dt \quad (3)$$

195 where μ is the multi-model mean ice-free date of the CMIP6 GCMs, σ is the standard
 196 deviation ice-free date of all CMIP6 GCMs, and t_0 is the beginning of each simulation.
 197 Because some GCMs do not project ice-free conditions in the 21st century, each probability
 198 is normalized by the number of GCMs used relative to the total number of GCMs, which
 199 makes this analogous to the cumulative frequencies of GCMs being ice-free. In this paper,
 200 we adopt the IPCC likelihood scale where ‘very unlikely’ means 0–10%, ‘unlikely’ means
 201 0–33%, ‘as likely as not’ means 33–66%, ‘likely’ means 66–100%, and ‘very likely’ means
 202 90–100%.

203 **3 Sources of uncertainty in model projections of Arctic sea ice**

204 We first apply Eq. (1) to simulations in Phase 6 of the Coupled Model Intercomparison
 205 Project (CMIP6) (Eyring et al., 2016) with Historical and SSP5-8.5 forcing (see Section 2
 206 for more details). Over all months, the proportion of variance across the GCMs that Eq. (1)
 207 accounts for varies between 70% and 95% during 2020–2100 (Fig. 2a). The period in which
 208 Eq. (1) accounts for the lowest fraction of intermodel variance occurs in early summer
 209 during the beginning of the 21st century, when approximately 70–80% of the intermodel
 210 variance is captured. Eq. (1) accounts for the most (>90%) intermodel variance in late fall
 211 and early winter, likely because model-to-model variations in climatological Arctic SIA are
 212 largest in the wintertime (Davy & Outten, 2020; Shu et al., 2020). Arctic SIA calculated
 213 from Eq. (1) also bears a striking similarity to the trajectory of each individual GCM for
 214 the summer months (Supplemental Figure S2), which is the primary season of interest in
 215 this study.

216 The ability of Eq. (1) to capture most of the intermodel variance suggests the three
 217 terms in Eq. (1) can be used to identify sources of intermodel spread in projections of Arctic
 218 SIA. Isolating the intermodel spread of each term (see Section 2 for more details) shows that
 219 in the near future, biases in present-day SIA (\bar{A}_c) account for approximately 70–80% of the
 220 total intermodel variance (Fig. 2b). In winter, the effect of mean-state biases persists
 221 much longer into the 21st century than in the summer, largely because sea ice remains
 222 present, whereas summer sea ice disappears in most GCMs by 2065. In summer, mean-state
 223 biases are important initially, accounting for 40–50% of the intermodel spread for the first
 224 decade beyond 2020, but their contribution quickly diminishes to approximately 20–30% by
 225 2050. The remaining intermodel spread arises from differences in local sea ice sensitivities
 226 (Fig. 2c) and Arctic warming (Fig. 2d). In late fall, model differences in the local sea ice

227 sensitivity account for approximately 30% of the intermodel variance at the end of the 21st
228 century. Notably, at the summer minimum, the spread in local sea ice sensitivity explains
229 little intermodel variance at the end of the 21st century. The majority of the intermodel
230 spread in September Arctic SIA projections at the end of the 21st century is associated
231 with differences in Arctic warming simulated by GCMs, which accounts for over 80% of the
232 intermodel variance. In winter, variations in Arctic warming begin to matter toward the end
233 of the 21st century and make up approximately 30–40% of the total intermodel variance.
234 Similar results are found for a medium emissions scenario (SSP2-4.5) and a low-emissions
235 scenario (SSP1-2.6), though the relative role of intermodel differences in Arctic warming
236 decreases and accounts for 40–60% of the total summer variance by the end of the 21st
237 century (Supplemental Figure S3–S4).

238 **4 Constraining model projections of Arctic sea ice**

239 We can use Eq. (1) in conjunction with observations to constrain the intermodel spread
240 in projections of Arctic SIA. Satellites have been reliably monitoring Arctic sea ice con-
241 centration since 1979, giving estimates of Arctic SIA for more than 40 years. Reanalysis
242 datasets similarly give relatively accurate estimates of Arctic temperatures going back to
243 the early 1950s, when the U.S. Navy and other national meteorological institutes began
244 regular, year-round monitoring of the Arctic. We quantify how these observations constrain
245 projections of an ice-free Arctic (defined as the first year when each GCM crosses the 1
246 million² km² SIA threshold) by fitting a Gaussian distribution to the GCM ensemble (see
247 Section 2 for more details). This is analogous to the cumulative frequencies of GCMs being
248 ice-free (Supplemental Figure S5).

249 **4.1 September**

250 We begin by focusing on September Arctic SIA projections in GCMs, based on Eq.
251 (1), without observational constraints. Under a high-emissions scenario (SSP5-8.5), CMIP6
252 GCM estimates for the terms on the right-hand side of Eq. (1) suggest that it is ‘likely’
253 (>66% probability) the Arctic will experience an ice-free September by 2057 and that it
254 is ‘very likely’ (>90% probability) the Arctic will experience an ice-free September around
255 2100 (Fig. 3a). Raw GCM output predicts that these ice-free dates will occur 3-5 years
256 earlier than Eq. (1) (Supplemental Figure S5), implying that Eq. (1) provides a relatively
257 accurate estimate of the simulated behavior.

258 Correcting for mean-state biases in GCMs by using Eq. (1) with the mean-state of
259 September Arctic SIA from 1979–2020 in observations rather than GCMs, brings forward
260 the ‘likely’ date by 4 years to 2053 and brings forward the ‘very likely’ by 30 years (Figure
261 3a). Note, this mean-state adjustment reduces the likelihood of seeing ice-free conditions
262 in the next few decades. Next, using the observed local sea ice sensitivity γ , rather than
263 that from each GCM in addition to the mean-state correction, moves the ‘likely’ date of an
264 ice-free Arctic forward by three more years to 2050. The ‘very likely’ date moves forward
265 by an additional 6 years to 2060. This indicates that GCMs tend to underestimate the local
266 sea ice sensitivity in September.

267 The monthly local sea ice sensitivity is not constant in time in the GCM simulations;
268 they systematically show increasingly negative values in the future. The more negative γ
269 values could arise from the fact that the relationship between sea ice thickness and area
270 is not perfectly linear. At higher thickness regimes, a change in Arctic temperature would
271 result in a smaller area change, whereas at lower thickness regimes, the same change in
272 Arctic temperature would result in a larger area change. Estimating γ from 1979 up until
273 a particular year yields an estimate of how the local sea ice sensitivity evolves in the fu-
274 ture according to state-of-the-art GCMs (see Section 2 for more details). With this added
275 guidance, the ‘likely’ date of seeing an ice-free Arctic in September moves forward by 4
276 years to 2046. This constraint moves forward the ‘very likely’ date of ice free conditions in
277 September by 5 years to 2055, which is close to 50 years sooner than the CMIP6 GCMs
278 suggest. Internal variability, which is calculated from a single-model initial condition large
279 ensemble as three standard deviations of the ice-free probability, adds uncertainty to the
280 ice-free date and implies an error range of approximately ± 10 years on these estimates (see
281 Section 2 and Table S2). That is, under a high-emissions scenario, our constraint suggests
282 that an ice-free September in the Arctic is ‘likely’ to occur between 2036–2056 and ‘very
283 likely’ to occur between 2045–2065.

284 The same observational constraints can be applied under medium- and low-emissions
285 scenarios. CMIP6 GCMs in conjunction with Eq. (1) suggest the ‘likely’ date of an ice-
286 free Arctic in September occurs in 2064 and beyond 2100 for medium- and low-emissions
287 scenarios, respectively (Fig. 3b-c). Applying the same observational constraints on \bar{A}_c and
288 γ shifts this date to 2051 and 2091 for medium- and low-emissions scenarios, respectively. In
289 both the medium- and low-emissions scenarios, correcting for mean-state biases pushes back
290 the date of an ice-free Arctic. Constraining the local sea ice sensitivity with observations

291 moves forward the date of ice-free conditions for the medium-emissions scenario, but it does
292 relatively little to the low-emission scenario. In both scenarios, the future evolution of the
293 local sea ice sensitivity (diagnosed separately for each emissions scenario) moves forward
294 the date of an ice-free Arctic. When compared to the CMIP6 output, the constraints shift
295 the ‘as likely as not’ (>33% probability) date for the medium-emissions scenario forward by
296 approximately 7 years and the ‘likely’ date forward by approximately 15 years (Fig. 3b).

297 4.2 Late summer and early fall

298 The seasonality of an ice-free Arctic is a feature of Arctic SIA projections that remains
299 important to quantify, as wildlife like polar bears depend on the number of ice-free days
300 (Molnár et al., 2020). Under a high emissions scenario, CMIP6 GCMs suggest that by 2081
301 the Arctic will ‘likely’ experience ice free conditions in July (Fig. 4a). Applying the same
302 constraints on \bar{A}_c and γ for July suggests the ‘likely’ date of an ice-free July is actually 2052,
303 approximately 30 years sooner than GCMs suggest. This is related to the fact that GCMs
304 have large biases in \bar{A}_c and γ in July when compared to observations. Internal variability
305 changes this estimate to between 2045 and 2060. For August, a similar picture emerges.
306 CMIP6 GCMs suggest the Arctic will ‘likely’ experience ice free conditions in August by
307 2060, but the constrained estimate is 2050 with a range of 2041 and 2059 due to internal
308 variability (Fig. 4b). The ‘very likely’ year is around 2060. All of these estimates are 10–30
309 years sooner than the GCMs suggest and the ‘very likely’ date moves forward by almost
310 50 years. October shows a similar picture to the other months. The ‘likely’ year of the
311 Arctic experiencing ice-free conditions is 2070 (Fig. 4d). Observational constraints of \bar{A}_c
312 and γ moves forward this year to 2059, more than 10 years sooner than GCMs suggest. The
313 ‘very likely’ date is around 2071, which is approximately 30 years sooner than raw GCM
314 projections.

315 Under SSP2-4.5 these constraints suggest the ‘likely’ date when the Arctic will expe-
316 rience an ice-free July occurs around 2062 (Fig. 4a). For SSP1-2.6, by the end of the
317 21st century it is ‘as likely as not’ that the Arctic will experience ice-free conditions in
318 July. Furthermore, the probability of seeing ice-free conditions from July to October is
319 greatly increased when compared to the raw output and will ‘likely’ occur around 2080 for
320 a medium-emissions scenario. For a low-emissions scenario, at the end of the 21st century,
321 the Arctic will ‘likely’ be ice free in September but not in other months. This suggests that

322 the emissions scenario matters for the length of the ice-free season, consistent with Jahn,
323 (2018).

324 **5 Discussion**

325 While previous studies have constrained the intermodel spread in Arctic SIA projections
326 (Wang & Overland, 2009; Boé et al., 2009; Massonnet et al., 2012; Notz & SIMIP Commu-
327 nity, 2020), most have done so by neglecting GCMs that poorly simulate present-day Arctic
328 sea ice. The fact that GCMs can match observations for the wrong reasons (e.g., Rosenblum
329 & Eisenman, 2017) suggests studies examining future projections should apply physically
330 meaningful and robust constraints, rather than neglecting GCMs that do not meet certain
331 observational criteria. This may explain why our results differ from the conclusions of Notz
332 & SIMIP Community (2020), who find that after applying observational constraints the ma-
333 jority of GCMs become ice-free by mid-century, even under a low-emissions scenario. Here,
334 we find that the majority of GCMs do not become ice-free until approximately 2080 under
335 a low-emissions scenario. These differences likely arise because we retain more intermodel
336 differences in the simulated amount of Arctic warming and use fewer ensemble members of
337 a single GCM.

338 This work, however, requires a few caveats. There are uncertainties associated with
339 our observational estimates of Arctic warming and Arctic SIA that may change how well
340 GCMs match observations, and change our observational estimates of γ , particularly at
341 monthly timescales (Niederrenk & Notz, 2018). We also did not explore the role of model
342 inter-dependency (e.g., Sanderson et al., 2015; Knutti et al., 2017) on these conclusions.
343 Investigation of how uncertainty in observations and model inter-dependency influence the
344 results here should be the subject of future work. Finally, we did not examine the causes
345 of Arctic warming in these GCMs. Previous work suggests GCMs have trouble simulating
346 circulation driven sea ice melt (e.g., Topál et al., 2020; Luo et al., 2021), which may have
347 accounted for 20–40% of observed Arctic sea ice loss (Ding et al., 2019). Future work should
348 study the role of model biases in influencing the evolution of the local sea-ice sensitivity.

349 **6 Summary**

350 This study introduces a simple framework to explain and constrain model projections of
351 Arctic SIA over the 21st century. We find that a simple model (Eq. 1), which approximates
352 future SIA based on present SIA and the sensitivity of SIA to Arctic temperatures, is able to

353 emulate the evolution of Arctic SIA with remarkable skill. This model accounts for 70–95% of
354 the intermodel variance in projections of Arctic SIA. Isolating the contributing factors shows
355 that the majority of the model uncertainty in projections of Arctic SIA arises from biases in
356 simulating present-day Arctic SIA. The remaining model uncertainty arises from differences
357 in the simulated amount of Arctic warming, with some contribution from differences in
358 the local sea ice sensitivity. This suggests that the degree of Arctic amplification and
359 representation of clouds in these GCMs (e.g., Meehl et al., 2020; Zelinka et al., 2020) may
360 be key to understanding the fate of Arctic sea ice.

361 Using observations to constrain the individual components of Eq. (1) moves forward
362 the date of an ice free Arctic by 10–35 years when compared to unconstrained projections.
363 Under a high-emissions scenario, the probability of seeing ice-free conditions in the Arctic in
364 September around 2035 is ‘as likely as not’, and the probability of seeing ice-free conditions in
365 the Arctic in September around 2068 is ‘virtually certain’ (>99% probability), which is much
366 sooner than climate models suggest. The fate of Arctic sea ice throughout the summertime
367 is similar. The probability of seeing ice-free conditions from July to October around 2059
368 is ‘likely’, and it is ‘very likely’ that the Arctic will experience ice-free conditions that
369 persist from July to October around 2070 under a high-emissions scenario. Thus, this work
370 highlights the importance of considering the length of the potential ice-free period when
371 assessing model projections, not just the date of seeing ice-free conditions in September.
372 Importantly, reducing emissions pushes back the expected dates of ice-free conditions. Under
373 a medium-emissions scenario, the Arctic will ‘likely’ only experience ice-free conditions from
374 July to October after 2080. Under a low-emissions scenario, the Arctic will ‘likely’ only
375 be ice free in September at the end of the 21st century. Hence, the emissions scenario
376 determines the length of the ice-free season. Overall, our results show how observations can
377 be used in concert with a simple model to constrain the date of seasonally ice-free conditions
378 in the Arctic Ocean.

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391 cal’, ‘SSP126’, ‘SSP245’, or ‘SSP585’. Code and data for this research is also available at
392 <https://doi.org/10.5281/zenodo.5177172>.

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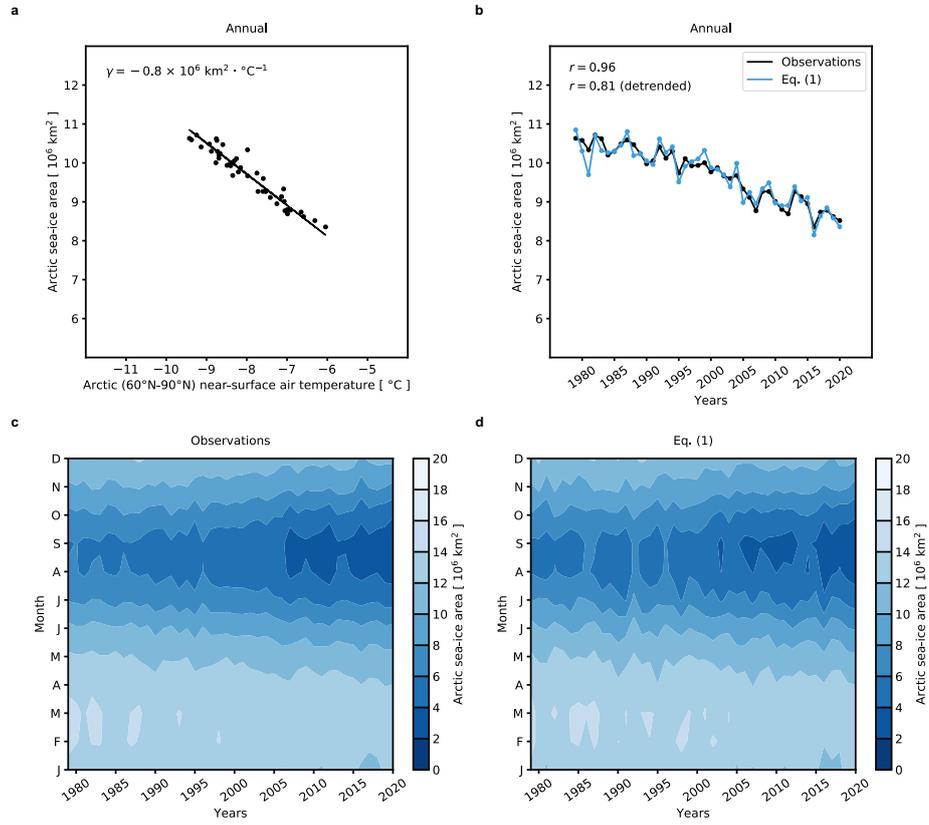


Figure 1. Applying the simple model (Eq. 1) to observations. (a) Scatter plot showing the relationship between observed annual Arctic (60°–90°N) near-surface air temperature and annual Arctic sea-ice area from 1979–2020, implying a local sea ice sensitivity of $\gamma = -0.80 \times 10^6 \text{ km}^2 \text{ } ^\circ\text{C}^{-1}$. (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 γ estimated for each month.

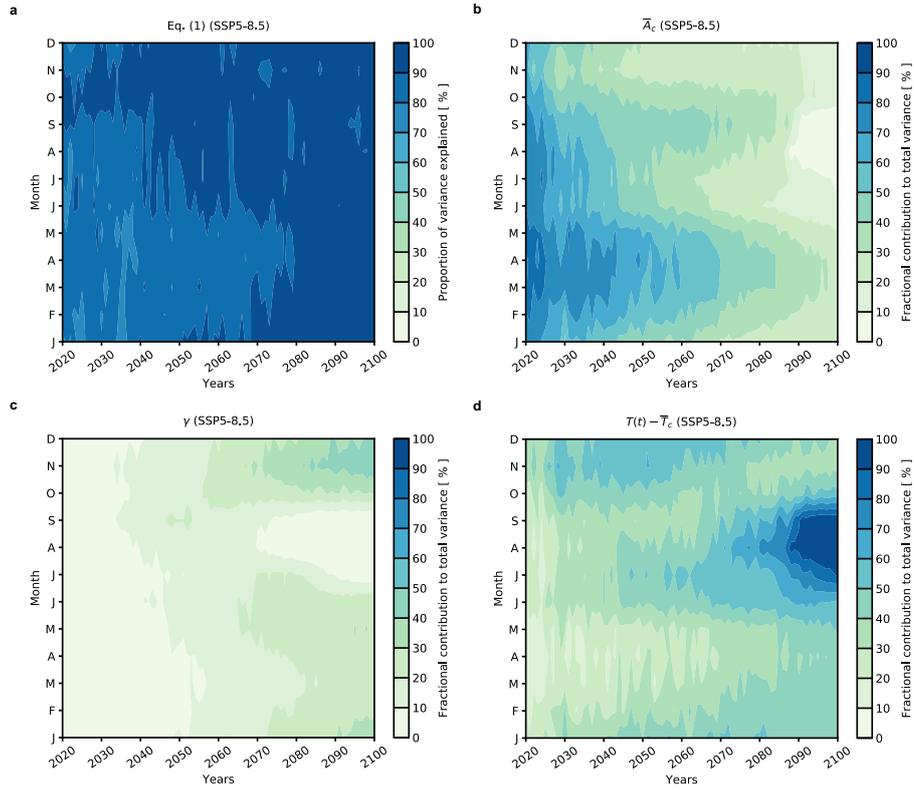


Figure 2. Partitioning intermodel variance in projections of Arctic sea-ice area. (a) The proportion of the intermodel variance (r^2 , where r is the Pearson correlation coefficient) in monthly Arctic sea-ice area from CMIP6 SSP5-8.5 simulations that is accounted for by Eq. (1) as a function of month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

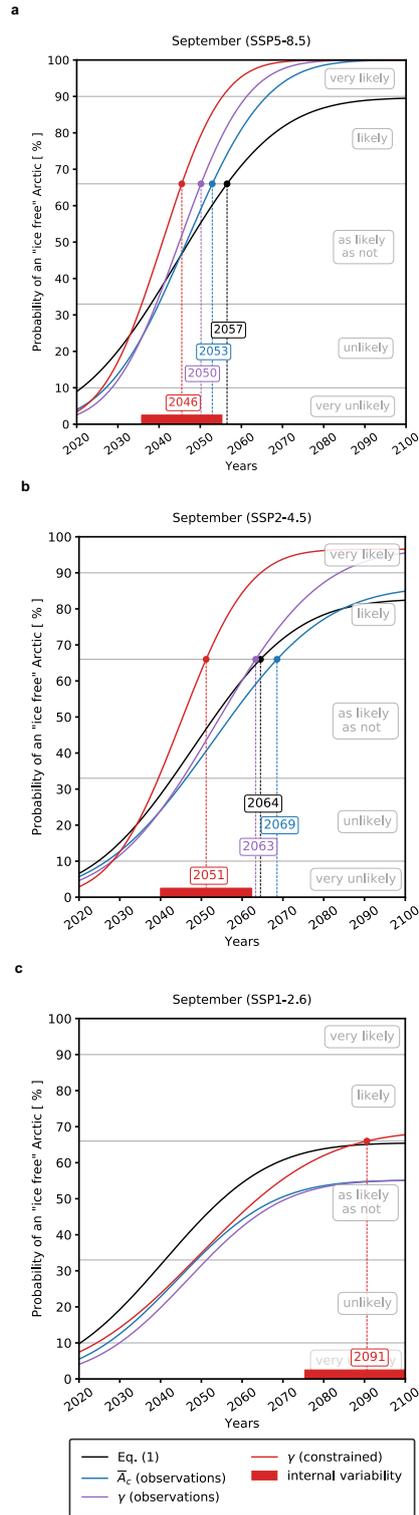


Figure 3. Probability of an ice-free Arctic in September. Cumulative probability density function for the year when the Arctic will experience ice free conditions in September for (a) SSP5-8.5, (b) SSP2-4.5, (c) SSP1-2.6. The black line is the unconstrained Eq. (1) using CMIP6. The blue line is constrained 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 CanESM5-LE.

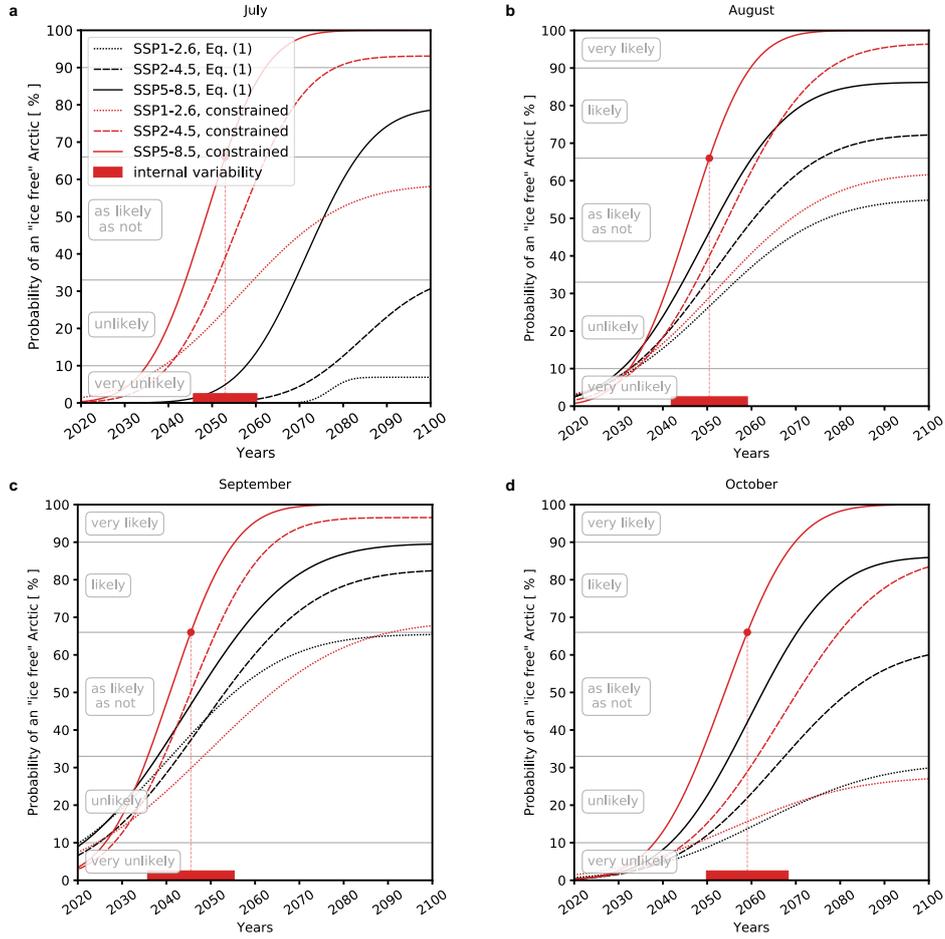


Figure 4. Probability of an ice-free Arctic from July to October. Cumulative probability density function for the year when the Arctic will experience ice free conditions in (a) July, (b) August, (c) September, and (d) October. The black line is the unconstrained Eq. (1) using CMIP6. The red line is the constrained output with the observed \bar{A}_c and γ , 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. The red shading denotes the range due to internal variability estimated from the CanESM5-LE.