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Review article

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Projections of an ice-free Arctic Ocean

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Abstract

Observed Arctic sea ice losses are a sentinel of anthropogenic climate change. These reductions are projected to continue with ongoing warming, ultimately leading to an ice-free Arctic (sea ice area <1 million km^2). In this Review, we synthesize understanding of the timing and regional variability of such an ice-free Arctic. In the September monthly mean, the earliest ice-free conditions (the first single occurrence of an ice-free Arctic) could occur in 2020–2030s under all emission trajectories and are likely to occur by 2050. However, daily September ice-free conditions are expected approximately 4 years earlier on average, with the possibility of preceding monthly metrics by 10 years. Consistently ice-free September conditions (frequent occurrences of an ice-free Arctic) are anticipated by mid-century (by 2035–2067), with emission trajectories determining how often and for how long the Arctic could be ice free. Specifically, there is potential for ice-free conditions in May–January and August–October by 2100 under a high-emission and low-emission scenario, respectively. In all cases, sea ice losses begin in the European Arctic, proceed to the Pacific Arctic and end in the Central Arctic, if becoming ice free at all. Future research must assess the impact of model selection and recalibration on projections, and assess the drivers of internal variability that can cause early ice-free conditions.

Sections

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Introduction

Arctic sea ice cover – including sea ice area (SIA)[1], sea ice extent (SIE)[2] and sea ice thickness[3,4] – has declined conspicuously since the beginning of satellite observations in 1978. Although losses have occurred in all seasons[5], reductions are greatest during summer, with SIA[6] declining by −0.078 million km^2 year^{-1} between 1979 and 2023. However, these reductions are not temporally consistent: summertime SIA losses between 1996–2012 are more than twice those over 1979–2023, reaching −0.17 million km^2 year^{-1}. Spatial variability also contributes to sea ice loss heterogeneity[7], with the largest reductions seen in the shelf seas of the Arctic Ocean (the Barents, Kara, Laptev, East Siberian and Chukchi Seas).

Given observed and projected warming[8], these sea ice reductions are set to continue such that the Arctic could become ice free. Indeed, climate models from the late 1970s already predicted the possibility of reaching summer ice-free conditions under sufficient warming[9], with current climate models suggesting that September is likely to be ice free before mid-century[10]. However, internal variability[11,12], physical differences between the models[13] and evolving definitions of 'ice free'[12] complicate accurate predictions, as demonstrated by the timing of ice-free conditions differing by more than 20 years owing to internal variability[12], by more than 100 years across models[10,14] or by decades depending on the definition used[12].

Regardless of prediction uncertainties, the transition to an ice-free Arctic signifies a regime shift from a perennial sea ice cover to a seasonal sea ice cover, or from a white summer Arctic to a blue Arctic[15] (Fig. 1). Such changes have probably not occurred for at least 80,000 years[16] (Box 1) and will have important impacts on the local and global climate and on ecological systems. For instance, replacing sea ice cover with open water modifies the radiation balance via reductions in albedo[17], in turn, accelerating and amplifying anthropogenic warming[18], especially in the Arctic[19–22]. Moreover, open-water areas and ice-free conditions allow for a larger fetch[23], increasing wave heights[24,25] and, thereby, coastal erosion around the Arctic Ocean[26–28]. From an ecosystem perspective, the transition towards a summer ice-free Arctic threatens the survival of sea ice-dependent mammals such as polar bears and seals[29–31], leads to increasing ocean productivity[32], and allows for the potential migration of some fish species from the sub-polar seas into the Arctic Ocean[33,34]. Economic activity in the Arctic could also increase owing to enhanced accessibility for shipping[35] and resource exploration[36]. Due to the multitude of impacts on an ice-free Arctic, it is important to understand the timing of when the Arctic could become ice free.

In this Review, we summarize the current understanding of an ice-free Arctic. We begin by discussing the drivers of sea ice loss, followed by available methodological approaches and corresponding uncertainties. Next, we outline predictions of an ice-free Arctic, including for September, months beside September and regional variability. We end with an outlook of future research needs. To quantify ice-free projections, we analyse monthly sea ice from select[10] Climate Model Intercomparison Project 6 (CMIP6)[37] models, hereafter referred to as 'select models', chosen on the basis of observations falling within the ensemble spread of each model for two key metrics[10]: the 2005–2014 September mean sea ice area and the observed sensitivity of sea ice area to cumulative CO_2 emissions over 1979–2014 (Supplementary Table 1). These select models are supplemented by large ensemble simulations from CMIP5 (ref. 38) and CMIP6.

Drivers of Arctic sea ice loss

Arctic sea ice changes are linked to a multitude of interconnected processes and feedbacks (Fig. 2). Atmospheric and oceanic heat transport into the Arctic are two processes that vary because of internal climate variability and externally forced changes[39,40]. Within the Arctic, various feedbacks are also at play[41]. In the case of forced anthropogenic changes, the majority of these local feedbacks are positive feedbacks, amplifying Arctic sea ice loss and warming[42], but their magnitude is uncertain and varies across models[43,44]. Dominant examples include the albedo feedback and lapse rate feedback. Negative feedbacks, such as the influence of ice thickness on ice growth rates[45], can somewhat mitigate ice loss, but not enough to counteract declining trends. The strength of these feedbacks can be climate state dependent[46,47], which means their relative strength will vary as sea ice changes.

The observed September sea ice loss is attributable to forced change from anthropogenic emissions[48,49], reinforced by internal variability[50]. Historical model simulations that apply subsets of external forcings (only natural forcings, only anthropogenic aerosol forcings, only greenhouse gas forcings) have enabled the attribution of forced changes in the climate, demonstrating that greenhouse gas emissions drove considerable ice loss, modestly offset by the cooling effects of anthropogenic aerosol emissions[51]. Thus, the magnitude of observed sea ice loss would not have been possible without anthropogenic greenhouse gas emissions[48] (Supplementary Fig. 1). Although CO_2 emissions were the most impactful drivers, the radiative effects of chlorofluorocarbons account for about 48% of forced September sea ice loss from 1979–2005 (ref. 52). Hence, the Montreal Protocol delayed the occurrence of the first ice-free Arctic by about 10 years (ref. 53). Although observed sea ice loss has a roughly linear relationship with global mean surface temperature[54,55] and with the cumulative carbon dioxide emissions[1], these relationships might not hold for the future given changes in the mix of external forcings that contribute to forced changes in regional Arctic warming and Arctic sea ice loss.

Internal variability has enhanced this observed sea ice loss[50]. Specifically, internal variability in atmospheric circulation is estimated to have reinforced the observed September ice loss by up to 50% (refs. 50,56,57). Atmospheric variability, thereby, overall accounts for about 75% of Arctic sea ice internal variability[58]. Ocean heat fluxes into the Arctic, however, are also important and might have helped stabilize September SIA between 2007 and 2023 (ref. 59).

Internal variability combined with forced sea ice loss and local positive feedback can lead to large multi-year changes in the Arctic sea ice, referred to as rapid ice loss events (RILEs)[60]. As Arctic sea ice becomes thinner, large areas of the ice pack are susceptible to melt out, resulting in increased summer ice area variability[61,62] and a higher likelihood of RILEs. These RILEs are driven by ocean heat transport variations[60,63], atmospheric circulation anomalies[64] or a combination of the two[65]. The surface albedo feedback and fall cloud feedbacks reinforce these events[66]. Notably, periods of limited ice loss or even increasing sea ice are also possible when internal variability counteracts anthropogenically forced change[50]. The evolution of these high-ice-loss and low-ice-loss events affects the trajectory by which Arctic summer ice-free conditions will be reached. The potential occurrence of high ice-loss events allows for the possibility of reaching ice-free conditions within a few years when starting from the average sea ice cover in the early 2020s.

Methods for predicting an ice-free Arctic

Predictions of an ice-free Arctic use different definitions or methods, each with their own inherent uncertainties. These approaches are now discussed.

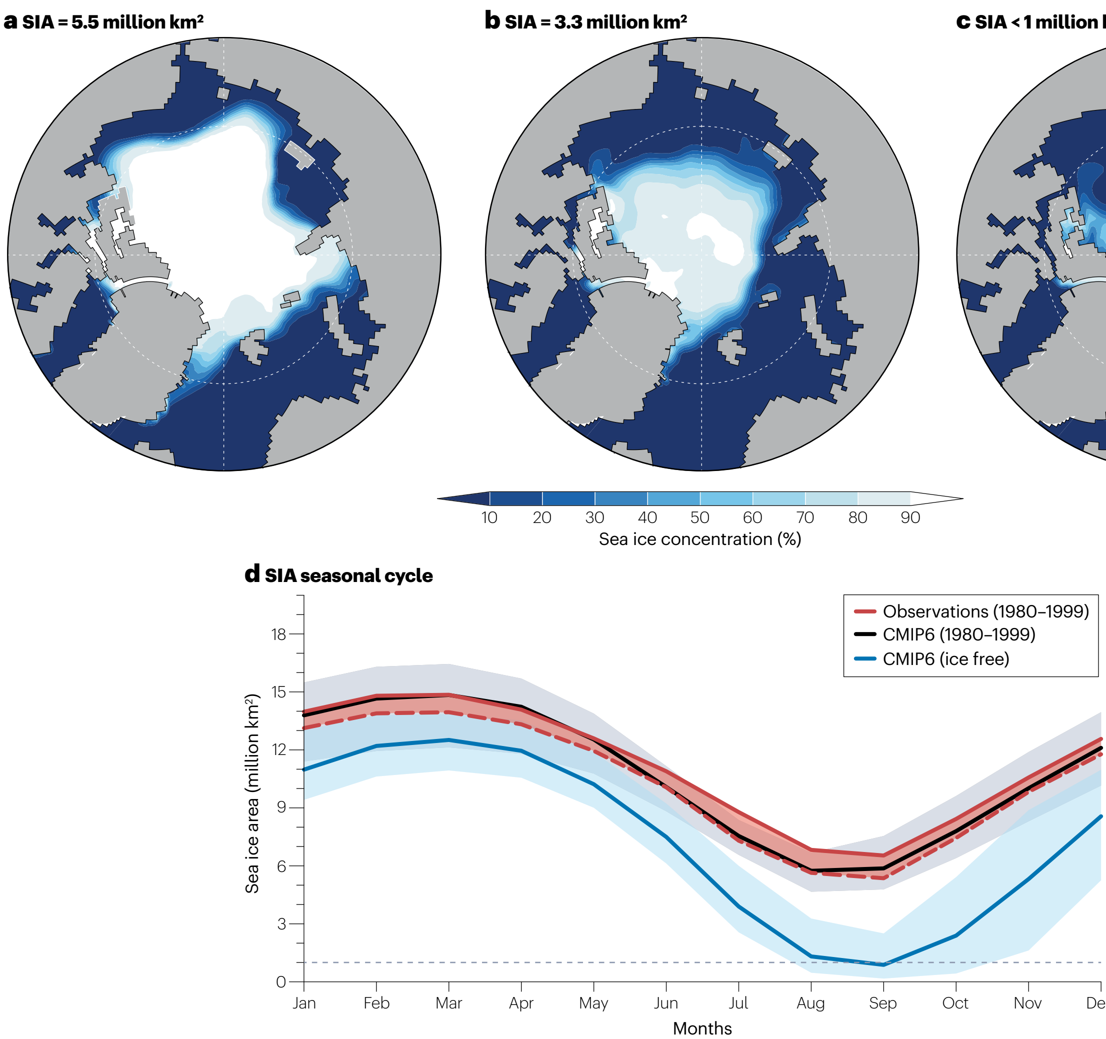

Fig. 1 | A white to blue Arctic. a, Pan-Arctic September sea ice concentration with a sea ice area (SIA) of 5.5 million km^2, typical for the 1980s. **b**, The same as in part **a**, but for 3.3 million km^2, typical for 2015–2023. **c**, The same as in part **a**, but for sea ice area of <1 million km^2, referred to as an ice-free Arctic. **d**, The climatological sea ice area seasonal cycles for 1980–1999 from satellite-derived observations[121] using the bootstrap[122] (solid red line) and NASA team[123] (dashed red line) algorithms, for 1980–1999 from select CMIP6 models[10] (black), and for a predicted ice-free September in select CMIP6 ensemble mean (blue). Red shading indicates uncertainty in the observed sea ice area (bounded by the seasonal cycle from the two algorithms), grey shading the CMIP6 ensemble spread for 1980–1999, and light blue shading the CMIP6 ensemble spread during the decade when the ensemble mean first goes ice free. Although sea ice area is reduced in all months of the year in the future, the loss is predicted to be greatest in September, but winter sea ice returns even after ice-free conditions are reached.

Contrasting definitions

The definition of an 'ice-free Arctic' has varied over time. Early on, it referred to the nearly complete disappearance of all sea ice, or zero SIE (refs. 9,60,67). However, as thick sea ice remains north of Greenland and the Canadian Arctic Archipelago more than a decade after the rest of the Arctic Ocean becomes ice free in September[60,68], a SIE threshold of 1 million km^2 became commonplace[48].

This 1 million km^2 threshold, however, can also introduce differences depending on the sea ice metrics it is applied to. For instance, an ice-free Arctic occurs earlier when the threshold is used with SIA rather than SIE (ref. 69) (Fig. 3a). Specifically, for the select CMIP6 models[10], ice-free conditions occur 0–47 years earlier (mean, mode and standard deviation of 8, 3 and 10 years, respectively) when using SIA instead of SIE. Moreover, differences occur when SIA calculations use a minimum threshold of 15% sea ice concentration[70,71], producing even earlier ice-free dates compared with using the standard SIA.

The temporal aspect of the underlying sea ice data also impacts the definition of ice free. Collectively, two clear definition categories emerge: predictions of the earliest ice-free conditions and predictions of consistently ice-free conditions (Fig. 3a), emphasizing internal variability and forced responses, respectively. Earliest ice-free conditions are obtained using unsmoothed monthly sea ice time series. This category focuses on the earliest possible occurrence of ice-free conditions, which could be a single event caused by internal variability once the mean sea ice state is low enough. By contrast, consistently ice-free conditions use smoothed data and, thus, focus on the likely occurrence

Box 1

The history of ice-free conditions in the Arctic

Although sea ice has been a defining feature of the Arctic Ocean since the Eocene (47 million years ago)[16], with perennial sea ice first appearing during the Miocene (around 13–14 million years ago)[16,124–126], ice-free conditions are not a first for the Arctic when assessed over the geological record. For example, before the Arctic became ice-covered, early ancestors of tropical plants and crocodiles thrived in the Arctic during the Cretaceous (over 70 million years ago)[127–129]. Moreover, proxy evidence suggest a return to ice-free summers in the Central Arctic Ocean during the late Miocene (approximately 5 million years ago)[130].

There is also evidence for ice-free conditions in the more recent geological past. For example, the last ice-free conditions in the Arctic likely occurred during the Eemian — the warmest period of the warmest quaternary interglacials — including marine isotope stage 5e (MIS 5e) (between 130,000 and 115,000 years ago) and potentially MIS 5a (around 80,000 years ago). At these times, proxy records indicate open water north of Greenland[131–135] and a northward shift of the tree line by hundreds of kilometres in Alaska and Russia[126,136]; note that paleo evidence for these changes is stronger for MIS 5e than MIS 5a.

By contrast, during the Holocene (the current interglacial that started 11,000 years ago), the Arctic Ocean likely retained its perennial sea ice cover[137,138]. However, there is evidence for regionally ice-free conditions in the Arctic during the mid-Holocene warm period that peaked around 6,000 years before present, particularly in the shelf seas of the eastern Arctic[16,138,139]. Thus, perennial sea ice was probably much reduced in the summer during the mid-Holocene and restricted to north of Greenland[138] where the oldest and thickest ice is found today[140,141].

Thus, when pan-Arctic ice-free conditions occur again in the next few decades, it will probably be a first for at least 80,000 years[132,133], if not for over 115,000 years[135]. The occurrence of pan-Arctic winter ice-free conditions, predicted to occur in the twenty-third century under extreme warming[115], would be a first for 47 million years, since the Arctic became sea ice covered in the Eocene[16].

of ice-free conditions based on the forced response. This category is heterogeneous, with examples using 5-year running means[54,67,72,73], using ensemble means[74], using five consecutive ice-free years[12,14,75,76], or likely ice-free conditions based on cumulative probabilities[77,78]. With all these methods, the predicted occurrence of first ice-free conditions is delayed compared with the earliest ice-free conditions (Fig. 3a). This diversity of definitions causes challenges in comparing existing ice-free predictions (Table 1), as definition differences affect the timing of ice-free conditions, ranging from a few years to well over a decade (Fig. 3a).

Cumulative probabilities provide a useful way to provide insight into both first ice-free and consistently ice-free conditions in a comprehensive manner. Indeed, when predictions of an ice-free Arctic are given in terms of cumulative probabilities, both the occurrence of the first possible ice-free Arctic (any percentage above zero) and consistently ice-free conditions can be inferred[76,77,79,80]. For the latter, different thresholds can be used to define consistently ice free, for example, >66% corresponding to the start of the 'likely' cumulative probability (Fig. 3, part **a** versus part **c**).

For regional ice-free conditions, it is not the 1 million km^2 threshold that is used to determine ice-free conditions, but instead a regional average sea ice concentration threshold. However, again there are differences in the threshold chosen. Specifically, a region has been considered ice free when the area-averaged sea ice concentration in the region falls below 15% (ref. 81) or reaches 6% (ref. 75).

Different prediction methods

In addition to definition choices, predictions of an ice-free Arctic can also be made using different methodological approaches, namely, using climate models or statistical models. Most Arctic ice-free predictions are made using projections from climate models[9,10,48,67,76,80,82,83]. Climate models explicitly simulate the evolution of sea ice, including dynamical and thermodynamical processes, albeit in an incomplete way owing to limited scientific understanding and/or computational constraints. Their model output can provide predictions of both early and consistently ice-free conditions depending on how the model output is analysed.

Statistical methods have also been used to provide predictions of an ice-free Arctic. Most of these predictions are based on observed linear relationships between global or Arctic temperature and sea ice cover[54,77,82,84,85], or CO_2 and sea ice cover[1,5]. Another approach is to use non-linear statistical relationships to make ice-free predictions[86]. Although useful, these statistical models possess several limitations. For example, the models typically assume that observed relationships will continue into the future, an assumption that might not be correct. Furthermore, they typically rely on linear relationships that represent the response of sea ice to forcing and, thereby, usually only provide predictions of consistently ice-free conditions and not early ice-free conditions. Inclusion of a statistical representation of internal variability can overcome this latter limitation[77,84,85]. In these cases, internal variability is usually based on standard deviations from observations or models, which means representation of rare sea ice loss events is dependent on how internal variability is estimated; using $\pm3\sigma$ (ref. 77) accounts for 99.7% of internal variability and, hence, excludes only truly rare events (0.3%), whereas using $\pm1\sigma$ (ref. 85) or $\pm2\sigma$ (ref. 84) excludes 32% or 5% internal variability, respectively, delaying the predicted occurrence of the earliest ice-free conditions.

Inherent uncertainties of predictions

Predictions based on climate models and statistical models each have uncertainties that are important to recognize. For climate model predictions, internal variability uncertainty, scenario uncertainty and model uncertainty are key considerations[87], whereas for statistical models, internal variability uncertainty (or neglecting internal variability uncertainty), scenario uncertainty, observational uncertainty and observed relationship uncertainty are important[85].

Internal variability prediction uncertainty is caused by the chaotic nature of the climate system[88]. The magnitude of internal variability uncertainty is around 20 years for predictions of a first ice-free Arctic[11,12] (but can be even larger for some models[89]) and slightly reduced by 8 years on average (Supplementary Fig. 2) for consistently ice-free conditions, as some internal variability is averaged out. This internal variability uncertainty cannot be eliminated, even with improvements in models and/or methodology, but could potentially be reduced by better understanding the underlying drivers of internal variability and refining predictions based on the potential predictability of those drivers[90]. Initial-value predictability (the predictability that arises from knowledge of an initial state) of sea ice might also allow for more precise predictions as the time of an ice-free Arctic comes closer, but this predictability is limited to seasonal–interannual timescales[91].

Scenario uncertainty is related to the evolution of future net emissions of greenhouse gases from all sectors, including land use. Given that these scenarios depend on future societal and policy decisions, it is an uncertainty that is not reducible. However, predictions based on degrees of anthropogenic warming[10,54,55,80,84] (Fig. 3d) or cumulative CO_2 emissions[1,10], rather than time, remove dependency on the specific emission scenario used.

Model uncertainty arises from structural differences in climate models — the choices made when building individual climate model components. These model (or structural) uncertainties are the largest source of uncertainty when predicting an ice-free Arctic[10,14,92]. Indeed, the ice-free prediction range due to model uncertainty in non-refined projections is over 100 years[10,14] (Fig. 3b). These model uncertainties are those that have the largest potential for reductions through model improvements. Yet, large multi-model spread has persisted for nearly two decades[10] despite improvements in sea ice model physics, highlighting that such improvements do not always yield immediate improvements in predictions.

Observational uncertainties in large-scale sea ice products refer to those associated with remote-sensing techniques. Depending on the methodology used, these uncertainties are linked to atmospheric interference, algorithmic uncertainties and the spatial resolution of sensors[93]. Comparing different products allows the magnitude of observational uncertainty to be estimated[10,85,93], which for September SIA is about 0.9 million km^2 over 1980–1999 (Fig. 1d).

Finally, uncertainties in observed relationships occur because of short time series[94] and/or uncertainty in whether historical relationships will continue in the future. For instance, extrapolating a short 12-year (1996–2007) observed linear relationship into the future led to prediction of the earliest possible ice-free Arctic in 2016 ± 3 years[95]. This prediction was not realized because the observed rate of sea ice decline is not constant in time, illustrating why linear extrapolation, especially of short time series, is not a reliable prediction method.

Refining model spread

Given the large uncertainties from structural model differences, there have been substantial efforts to reduce multi-model spread in ice-free projections. These approaches include using model selection[10,14,48,71,96–98], model weighting[13,74,92], emergent constraints[70,73], and model recalibration or constrained estimation[55,78,99], although no consensus on the best approach exists yet[14,55].

Model selection describes the use of a subset of the best models, whereas model weighting includes all models but weights the best models more heavily. Various metrics have been used for model selection or weighting, largely the mean, seasonal cycle and trends of SIA or SIE, the rates of warming or cumulative CO_2 emissions[10,14,48,92], and sea ice-based emergent constraints[70,73]. However, other metrics also show promise. For instance, model selection based on the relationship between summer SIA and April sea ice thickness narrowed CMIP6

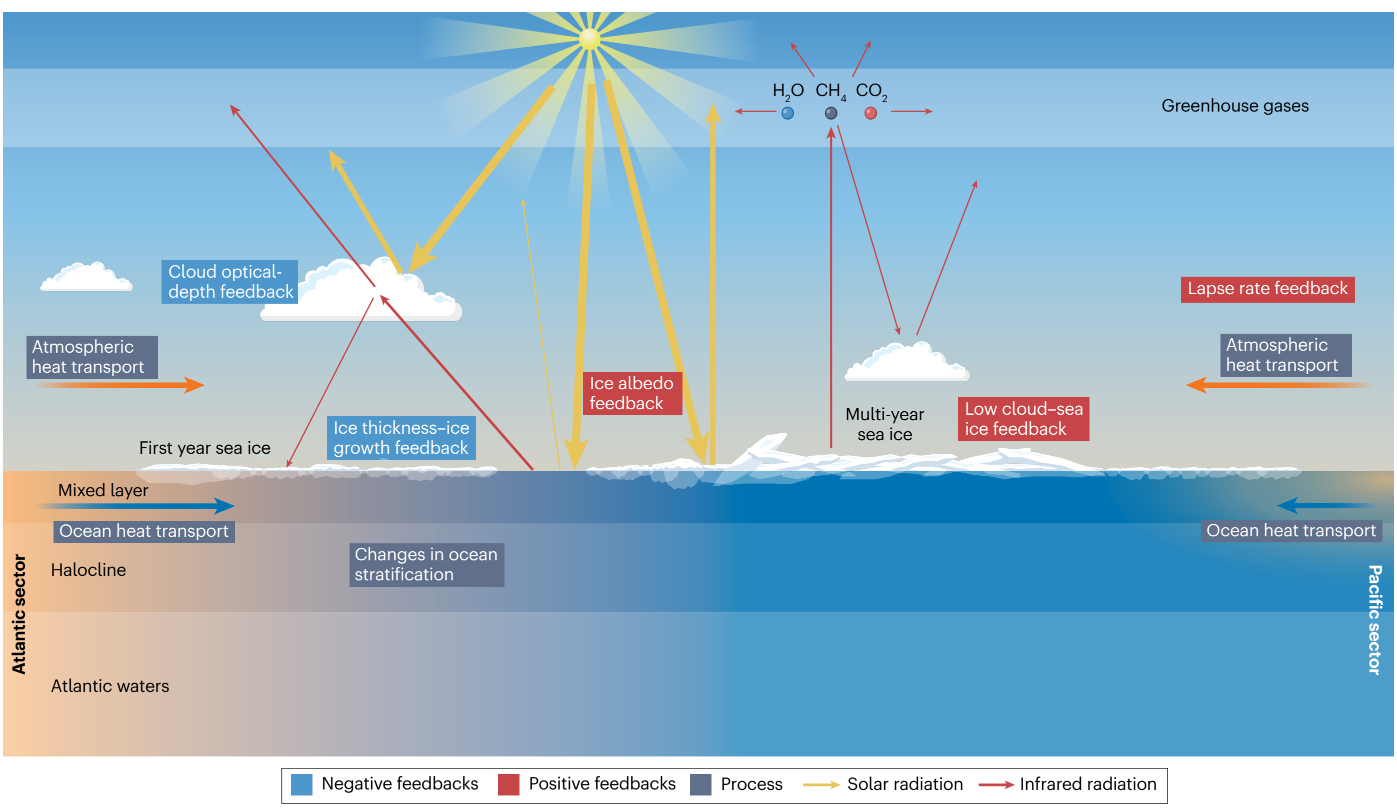

Fig. 2 | Processes and feedbacks driving Arctic sea ice loss. The highly coupled processes and feedbacks that affect Arctic sea ice in response to anthropogenic warming.

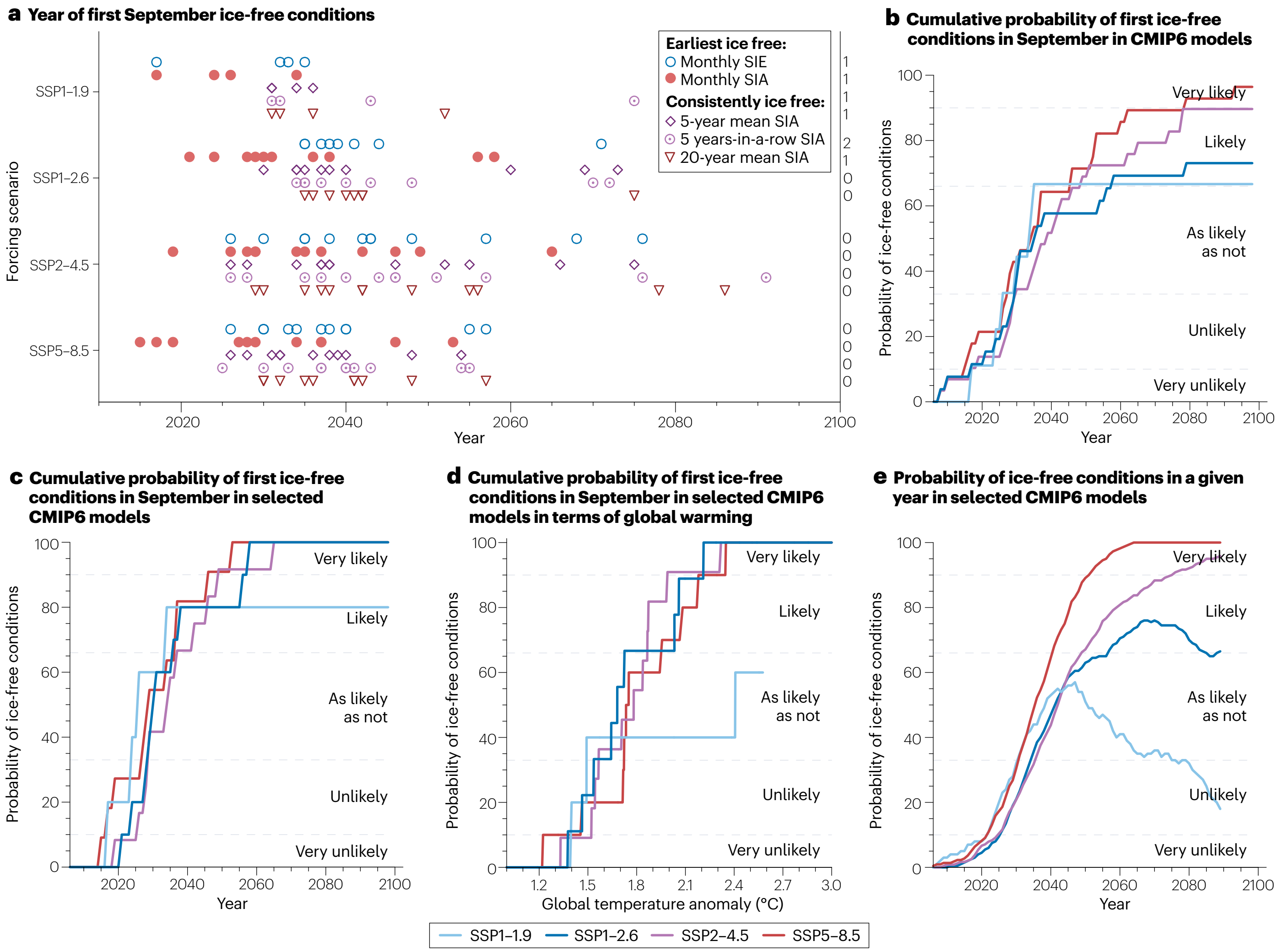

Fig. 3 | Sensitivity of ice-free Arctic timing to definitions and model selection. a, Year of the earliest ice-free September for 'selected CMIP6 models'[10] (Supplementary Table 1) based on different emission scenarios and definitions of ice free: 'Earliest ice-free conditions' use unsmoothed monthly sea ice area or sea ice extent (monthly SIA and SIE, respectively); 'Consistently ice-free conditions' use 5-year or 20-year smoothed sea ice area, or the first year after which the Arctic is ice free for 5 years for unsmoothed sea ice area (5-year mean, 20-year mean and 5 years in a row, respectively). Numbers on the right *y*-axis indicate the number of models that do not go ice free by 2100 for a given model, definition or scenario. **b**, The fraction of CMIP6 models that have reached ice-free conditions at least once in the monthly mean September sea ice area by a given year under a given forcing scenario — the cumulative probability of first ice-free conditions — and their likelihood according to the Intergovernmental Panel on Climate Change (IPCC) definitions. **c**, The same as in part **b**, but for the selected CMIP6 models in part **a**. **d**, The same as in part **c**, but the fraction of selected CMIP6 models that are ice free for a given temperature anomaly (using a 5-year smoothed mean to reflect the level of forced warming rather than individual year temperatures), with the anomaly calculated relative to each of the models 1850–1899 global temperature. **e**, The fraction of selected CMIP6 models that are ice free in a given year, smoothed by a 20-year running mean. Although definition differences and model selection influence the specifics of ice-free predictions, they all indicate that ice-free conditions tend to occur at least once by 2050 under all assessed scenarios, and become a frequent occurrence thereafter under all scenarios except SSP1-1.9.

projection uncertainty more than any previously used sea ice metrics[71]. Similarly, northward ocean heat flux as a selection parameter moved predictions 10 years earlier compared with sea ice-based parameters alone[98]. The importance of other oceanic variables in model weighting and selection also needs to be assessed, particularly Arctic Ocean stratification[100,101] and the properties of underlying warm Atlantic water[100,102] which have known biases in CMIP6 models.

Constrained model projections, also referred to as model recalibration, refer to the adjustment of climate model projections using observations. Thus, rather than selecting some models and using those as they are, model recalibrations modify the model-produced projections. Different recalibration methods influence the projected timing of ice-free conditions, as demonstrated by earlier ice-free dates when scaling the simulated SIA responses to greenhouse gas forcing[78], whereas a recalibration of the SIE sensitivity to atmospheric circulation leads to later ice-free dates than unconstrained projections[99] (Table 1).

Owing to differences in the underlying data and the definition of used ice-free condition, it is not currently possible to directly compare the effect of different model selection or refinement methods on ice-free projections. Thus, there is a need for dedicated intercomparisons to assess such effects. These efforts would allow the creation of a common set of metrics to use to select and/or refine sea ice projections, as well as establish a common ice-free definition to use going forward. As part of that process, it is crucial to not confuse precision with accuracy, as more precise projections are not by default better and can indeed be worse if, for example, the influence of internal variability is neglected.

Predictions of an ice-free Arctic

Considering definition differences and corresponding uncertainties, pan-Arctic ice-free predictions for September, ice-free conditions for months outside of September, and regional ice-free conditions are now discussed.

Pan-Arctic predictions for September

Most predictions for an ice-free Arctic focus on September, the month of lowest seasonal SIA and, thus, the first to reach ice-free conditions. These predictions indicate that the earliest ice-free conditions could potentially occur in the 2020s to 2030s and are likely going to occur by 2050 (ref. 10) (Table 1; Fig. 3c). However, there is large variability in these predictions, ranging from the 2010s to >2100 (refs. 10,14). Refined projections — through model selection, weighting and constraining — reduce this uncertainty to 2015–2050 (refs. 10,74,78,96). In terms of temperature, the earliest ice-free conditions could occur for warming >1.3 °C, are likely to occur for warming of 1.8 °C (Table 1; Fig. 3d), and exhibit a range of 0.9–3.2 °C (ref. 10) that can be refined to 1.3–2.9 °C (refs. 10,74,78,96).

For these earliest September ice-free conditions, there is no influence of emission scenario[10,69,74]. Indeed, all scenarios exhibit the possibility of earliest ice-free conditions from the 2010s or from a warming of 1.3 °C (Fig. 3c,d). This consistency arises owing to the short lead time and resulting small difference between emission trajectories[103,104]. Accordingly, the occurrence of the earliest ice-free conditions will be determined by internal climate variability[12] once the mean sea ice state is low enough. For example, conditions similar to those that caused the record 2007 (ref. 105) and 2012 (ref. 106) September minimums could lead to the drop of sea ice below the 1 million km^2 threshold once mean SIA is ≤2 million km^2. Early ice-free conditions could also be the result of a multi-year RILE (refs. 60,63) that could lead to ice-free conditions from an even higher mean sea ice state. However, internal variability (and resulting large single-year or multi-year events) can either enhance or oppose the forced response[50] and, hence, could delay the occurrence of ice-free conditions past the predicted earliest ice-free conditions[12].

Despite no impact of emission scenarios on the timing of an earliest ice-free Arctic, there remains a small chance that ice-free conditions can be avoided. In particular, if warming is limited to <1.5 °C or only exceeds 1.5 °C for a short time, there is a <10% chance that the Arctic does not become ice free[76,79,80,85,107,108], as in Shared Socioeconomic Pathway (SSP) 1-1.9 (Fig. 3d).

Warming levels also affect the frequency of ice-free conditions re-occurring after a first ice-free September[76,80] (Fig. 3e). For instance, if ice-free conditions occur for warming of ≤1.5 °C, they would likely not re-occur for several decades[76,107]. Yet, for warming >2 °C and >3 °C, September ice-free conditions would likely re-occur every 2–3 years[76,80,107] or almost every year[76,80], respectively; in the latter case, these changes are comparable to what is seen for the select CMIP6 models under SSP2-4.5 and SSP5-8.5 (Fig. 3e). Notably, if temperatures decrease again, probabilities of ice-free conditions in a given year will also decrease, as evident for SSP1-1.9 (Fig. 3e). Hence, no irreversible sea ice tipping point exists for summer Arctic sea ice[109–111].

Consistently ice-free conditions are expected by mid-century, potentially under all warming scenarios[78]. Predictions for consistently ice-free conditions range from 2023 to 2085, with refined projections of 2035–2067 (Table 1); the reduced uncertainty compared

Table 1 | Predictions of an ice-free Arctic from the literature

Method	Earliest ice free[a]	Consistently ice free[b]	Ref.
Projections in terms of time			
CMIP3 models	2050 to >2100	–	118
Select and adjusted CMIP3 models	2018–2074[e]	2037	48
Recalibrated CMIP3	–	2070[c,e]	54
Select and adjusted CMIP5 models	2021–2043	2035	96
Select CMIP5	–	2041–2060	14
Weighted CMIP5 models	2032–2046[c]	2039–2045[c]	74
CMIP5	–	2045–2070	75
Weighted CMIP5	–	2062	92
CMIP5 large ensembles	–	2023–2079	72
Select CMIP5	–	2044–2067	73
Constrained estimation of CMIP5	–	2056–2060	119
CESM1-LE	2032–2053	2040–2056	12
CESM2	2010–2042	–	69
CMIP6	<2014 to >2100[c]	–	10
Select CMIP6	2015–2052[c]	–	10
Select CMIP6	–	2035[c]	98
Select CMIP6	–	2043[c,d]	71
Obs-constrained CMIP6	2030s–2050s[c]	2040[c,e]	78
Statistical model, CMIP3 and obs	–	2066–2085	67
Statistical model, CMIP6 and obs	–	2036–2056[c]	77
Statistical model	–	2039	86
Projections in terms of warming			
Recalibrated CMIP3 and obs sea ice sensitivity	–	2.8 °C[c,e]	54
Observed sea ice sensitivity	–	1.8 °C[e]	120
Sea ice sensitivity and MPI-ESM	1.5 °C[c]	2.0 °C[c]	85
Bias-corrected CESM1-LE	1.5 °C	2.5 °C[e]	76
Constrained CanESM2	1.5 °C	–	80
CMIP6	0.9–3.2 °C[c]	–	10
Select CMIP6	1.3–2.9 °C[c]	–	10
Observed sea ice sensitivity	1.5 °C[c]	<2 °C[c]	84

Estimates are based using the high-emission scenario from each CMIP: SSP5-8.5 for CMIP6, RCP8.5 for CMIP5 and A1B for CMIP3. CESM, Community Earth System Model; CIMP, Climate Model Intercomparison Project; LE, large ensemble; obs, observed; RCP, Representative Concentration Pathway. [a]Earliest ice free: ice-free conditions diagnosed from unsmoothed time series. [b]Consistently ice free: ice-free conditions that exist in the ensemble mean, the multi-year running mean or for several years in a row. [c]Value based on sea ice area. [d]Study excludes areas of sea ice with less than 15% when quantifying sea ice area. [e]Values that were read from figures or calculated relative to a different baseline than published.

Glossary

Albedo
The fraction of incoming shortwave solar radiation that is reflected by a surface, ranging between 0 and 1.

Internal variability
The variability in the climate system attributable to the chaotic nature of the climate system.

Negative feedbacks
Dampening feedbacks in the climate system, reducing an initial perturbation.

Positive feedbacks
Amplifying feedbacks in the climate system, enhancing an initial perturbation.

Sea ice area
(SIA). The total area of sea ice present, without any threshold, calculated as sea ice concentration multiplied by grid area and summed over all Northern Hemisphere grid boxes. Note that sometimes, sea ice area is calculated only for grid cells with at least 15% sea ice cover.

Sea ice extent
(SIE). The area of all grid boxes that have at least 15% sea ice concentration, calculated as sea ice concentration multiplied by the area of all grid boxes with 15% or more sea ice concentration.

Sea ice sensitivity
The change in sea ice area divided by the change in global or Arctic temperature or cumulative CO_2 emissions over the same time period.

Shared Socioeconomic Pathway
(SSP). A forcing scenario that is part of the Scenario Model Intercomparison Project of CMIP6.

Tipping point
An irreversible change in an environmental condition.

with the earliest ice-free conditions is linked to the averaging out of some internal variability (Supplementary Fig. 2). In terms of warming, these conditions begin to occur at a global temperature increase of ≥1.8 °C (Table 1). Although consistently ice-free conditions potentially occur under all scenarios[78] (Fig. 3c), the strength of the forcing has some effect on the timing of consistently ice-free conditions[78] and, hence, also the interval between the earliest and consistently ice-free conditions (Fig. 3a). For example, although the difference between predictions of the earliest ice-free conditions and consistently ice-free conditions is around 10 years for SSP5-8.5, it is at least 15 years for SSP1-2.6 (Fig. 3a).

All previous predictions of ice-free conditions used monthly means as their underlying base data. Yet, the first time SIA dips below the 1 million km^2 threshold will be detected in daily satellite observations. SIA-based calculations from the CESM2-LE (ref. 112) suggest that the first occurrence of daily ice-free conditions happens, on average, 4 years prior to the ice-free September monthly mean (Supplementary Fig. 3), with a range of 0–18 years. Of the CESM2-LE members, 56% exhibit daily ice-free conditions earlier than monthly ice-free conditions (Supplementary Fig. 3b), whereas 44% of the CESM2-LE members experience daily and monthly ice-free conditions for the first time during the same year. Differences of 10 years or more, thereby, occur in 20% of the CESM2-LE members, with the largest differences occurring for ensemble members that have relatively late monthly mean ice-free conditions (Supplementary Fig. 3b). The earliest ice-free conditions in daily observations could, thus, occur even earlier than predicted based on monthly analysis of CMIP6 models and, hence, potentially in the 2020s (Fig. 3c).

Seasonality of reaching ice-free conditions

Although ice-free conditions are first expected in September, they could extend into other months[5,76,78,84,85]. The duration of this ice-free period has direct bearing on the resulting impacts: ice-free conditions that begin earlier in the summer strengthen the ice albedo feedback[47], increase early open-water areas and, thereby, ocean heat uptake, subsequently delaying fall freeze-up[113] and extending the ice-free season into late fall[5,76,84].

Generally, ice-free duration beyond September exhibits pronounced sensitivity to the warming level and, thus, emission scenario. For example, there is a possibility of occasional ice-free conditions in August and October with <2 °C warming (or SSP1-1.9) (refs. 76,85), extending into July with ≥2.5 °C warming[85] (or SSP1-2.6) and into November with ≥3.5 °C warming[76] (or SSP2-4.5) (Fig. 4). In some select CMIP6 models under SSP5-8.5, first ice-free conditions also occur in December, January, May and June during the second half of the twenty-first century (Fig. 4d) when warming exceeds 3.5 °C (ref. 114).

Intuitively, consistently ice-free conditions exhibit the same temperature sensitivity as first ice-free conditions but with delayed emergence. Consistently ice-free conditions likely emerge in August with ≥2.5 °C warming, October with ≥3.5 °C warming and November with ≥4 °C warming[76,85]. These sensitivities translate to differences across scenarios. For the selected CMIP6 models forced with SSP2-4.5, the ice-free season is expected to span 3 months per year by 2100 (as determined by continuous likely (>66%) ice-free conditions): ice-free conditions emerge in August by approximately 2055 and in October by approximately 2080 (Fig. 4c). In contrast, the likely ice-free season is expected to span 6 months for SSP5-8.5: beyond September, continuous ice-free conditions emerge in August by approximately 2050, in October by approximately 2055, in November by approximately 2070, in July by approximately 2075 and in December by approximately 2090 (ice-free conditions in July to October become very likely or virtually certain by 2100) (Fig. 4d). Consistently ice-free conditions are not expected beyond September for SSP1-1.9 (Fig. 4a) or SSP1-2.6 (Fig. 4b). In terms of CO_2 emissions, consistently ice-free conditions are predicted to begin to occur in July to October for an additional 1,400 Gt CO_2 relative to 2016 levels, and in November for around 3,000 Gt CO_2 (refs. 5,84).

With further warming, the Arctic could become ice free year-round. However, consistently ice-free conditions year-round are not anticipated until atmospheric CO_2 levels reach approximately 1,900 ppm (ref. 115), which are not expected until the twenty-third century under the strongest emission scenarios.

Regional variations of ice-free Arctic conditions

In addition to the seasonal sensitivity of ice-free projections, regional variability in ice-free timings are also expected. However, there are limited explicit predictions of these regional ice-free conditions, and those that do exist focus on consistently ice-free metrics[75,81]. In addition, regional assessments possess uncertainties greater than the pan-Arctic given larger internal variability (as averaging over smaller regions) and a reduced chance for compensating biases[75,81]. Accordingly, any projected dates of regional ice-free conditions are quite dependent on the underlying models and on whether model selection was performed, as well as on the exact definition of what constitutes ice-free conditions[75,81]. Thus, differences are apparent between CMIP5 and CMIP6, with earlier regional ice-free dates in CMIP6, potentially at least partially because of requiring only >85% open water[81] versus 94% open water[75] to consider a region ice free.

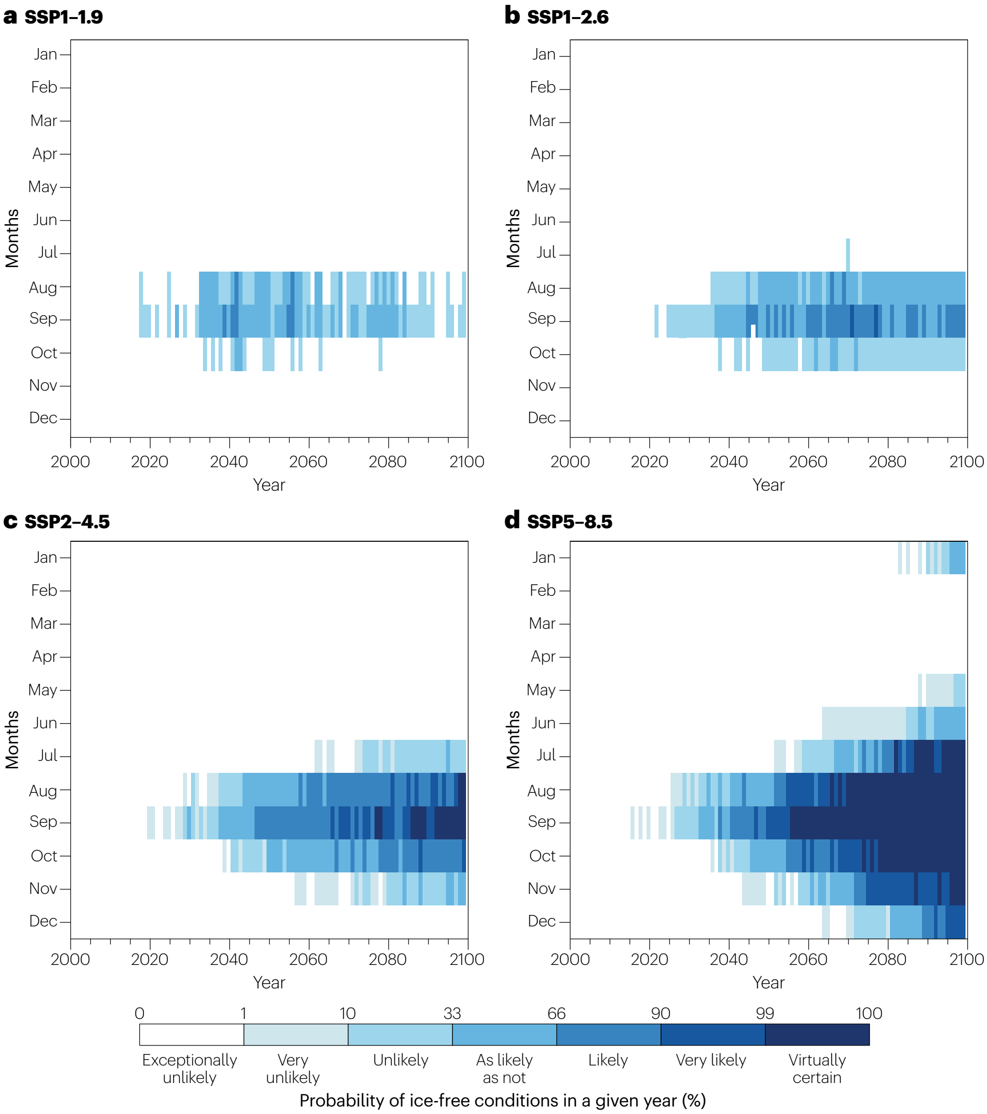

Fig. 4 | Probability of ice-free conditions in all months of the year. a, The probability of ice-free conditions in a given year and month without any smoothing for selected CMIP6 models[10] forced with SSP1-1.9. The probability is given using the IPCC terms and percentage values. The earliest ice-free conditions can be inferred when any probability of ice-free conditions exists, whereas consistently ice-free conditions start to exist when the probability in a given year reaches the likely category. **b**, The same as in part **a**, but for SSP1-2.6. **c**, The same as in part **a**, but for SSP2-4.5. **d**, The same as in part **a**, but for SSP5-8.5. There are large differences in how likely an ice-free Arctic is to occur in the months of a given year depending on the forcing scenario, with the possibility of ice-free conditions limited to 3 months under SSP1-2.6 and SSP1-1.9, 5 months under SSP2-4.5 and 9 months under SSP5-8.5.

Despite uncertainty in the timing, CMIP5 and CMIP6 models generally exhibit the same progression of consistently ice-free conditions around the Arctic[75,81]. Across all scenarios, September ice-free conditions start in the European Arctic shelf seas, with the Barents Sea and Kara Sea followed by the Laptev Sea, proceed to the Chukchi Sea, East Siberian Sea and Beaufort Sea (the Pacific Arctic), and end in the central Arctic[75,81]. Specifically, September regional ice-free conditions in the Barents Sea and Kara Sea are simulated to exist from August to October prior to 2015, with the Laptev Sea, East Siberian Sea and Chukchi Sea following in the 2020s and 2030s, followed by the Beaufort Sea in the 2030s and 2040s, under both SSP1-2.6 and SSP5-8.5 (ref. 81). The central Arctic could become ice free in September between 2040 and 2060 under SSP5-8.5 (ref. 81) and in the 2060s to 2100 in SSP2-4.5, while avoiding consistently regional ice-free conditions in the central Arctic under SSP1-2.6 and SSP1-1.9 (Fig. 5).

With only a small scenario impact on the timing of consistently ice-free conditions in the shelf seas, the main impacts of scenario differences are the duration of ice-free conditions in the shelf seas and whether and for how long the Central Arctic becomes ice free (Fig. 5). Specifically, the ice-free season is limited to 3 months a year by 2100 under SSP1-2.6 in the Laptev, East Siberian, Chukchi and Beaufort Sea, but lasts 7–8 months under SSP5-8.5 (ref. 81). In the Kara Sea, the difference between these two scenarios is 5 versus 9 months, whereas in the Barents Sea, it is 9 months versus ice free year-round[81]. Regional ice-free conditions in the Central Arctic only occur for SSP5-8.5 and SSP2-4.5, with the consistently ice-free season limited to August and September in SSP2-4.5, but extending for over 5 months under SSP5-8.5 (Fig. 5).

Summary and future perspectives

Arctic sea ice has declined substantially since the beginning of the satellite observations in 1978, and is projected to continue to do so into the future. Indeed, earliest ice-free conditions, defined as a single occurrence of ice-free conditions in the monthly mean data, might occur in the 2020s or 2030s for September, and are likely to

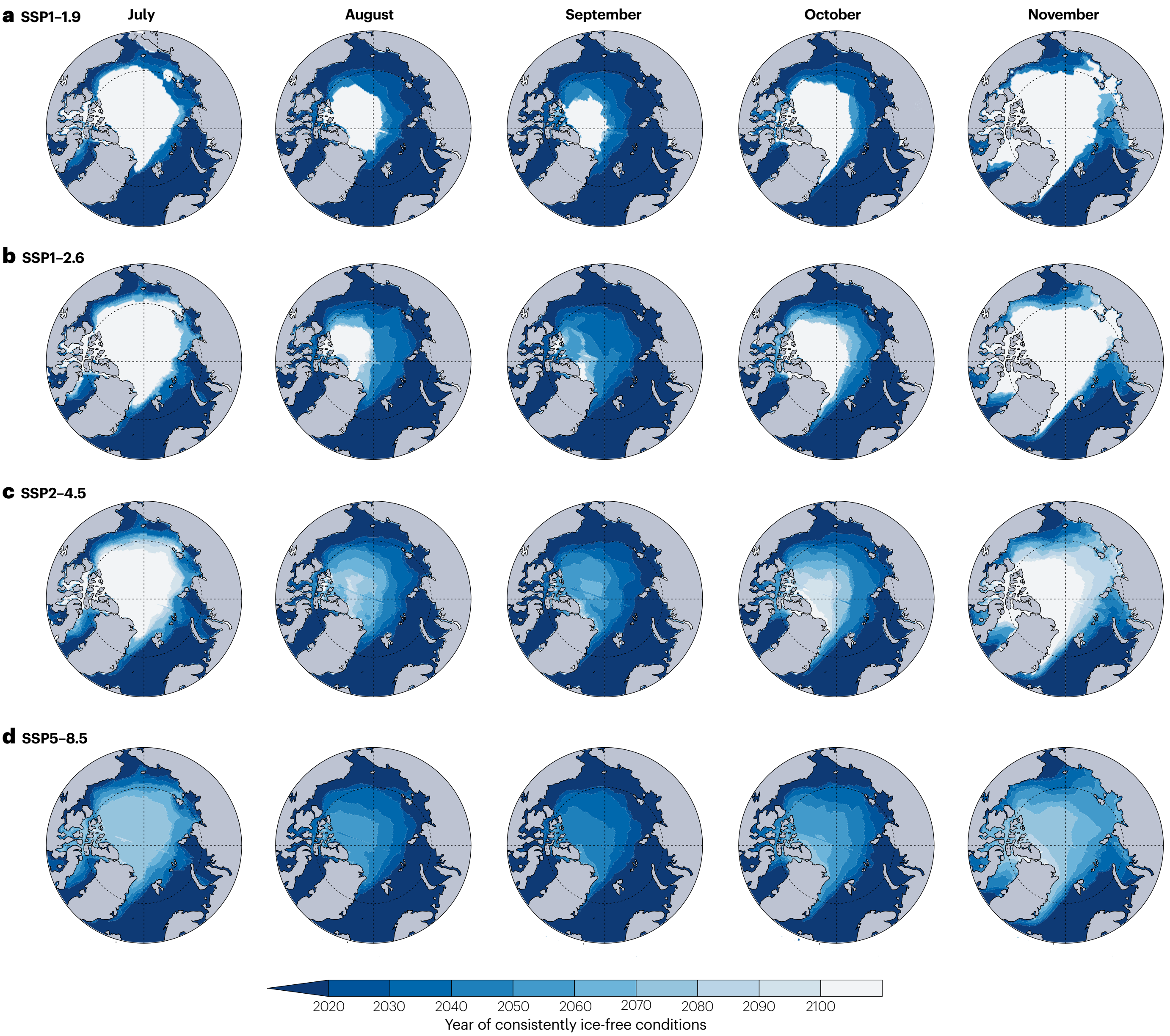

Fig. 5 | Regional ice-free conditions. a, Year sea ice is consistently ice free for July to November for SSP1-1.9, calculated as the first time sea ice concentration (SIC) in each grid is below 15% in a given month in the ensemble mean[81] of the selected CMIP6 models[10]. Bright white areas indicate regions that retain ice cover with more than 15% SIC in 2100, whereas dark blue areas indicate regions that became ice free before 2020 or that never had ice cover. **b**, The same as in part **a**, but for SSP1-2.6. **c**, The same as in part **a**, but for SSP2-4.5. **d**, The same as in part **a**, but for SSP5-8.5. Forcing scenarios have a big impact on the regional sea ice loss, with no ice-covered regions expected to remain between July and November by 2090 under SSP5-8.5, but some ice-covered regions remaining for every month under SSP1-1.9.

occur by mid-century[10] independent of emission scenario[10,76,78,80]. Consistently ice-free conditions, which refers to the transition to a frequently ice-free Arctic, are expected to occur between 2035–2067 under the high-emission scenarios, with a small delay possible for lower-emission scenarios. At the regional scale, these losses will begin in the shelf seas of the European Arctic, proceeding into the Pacific Arctic, and, under SSP2-4.5 and SSP5-8.5, end in the central Arctic. Ice loss is also expected beyond the months of September, particularly the shoulder months of August and October, but with marked temperature sensitivity. Thus, greenhouse gas mitigation strongly affects ice-free conditions, determining how often, for how long and where the Arctic will lose its sea ice cover. In particular, under the low-warming scenarios (SSP1-2.6), with warming remaining well below 2 °C, ice-free conditions could remain an exception rather than the new normal[76]. Furthermore, sea ice recovers quickly when temperatures drop[109–111], so if the world reaches sufficient negative emissions to lead to a global warming of less than 1.5 °C, ice-free conditions could disappear again in the future.

As the earliest possible date of an ice-free Arctic approaches, clear communication is key. Predictions must differentiate between those of consistently ice-free conditions (or likely (>66%) ice-free conditions) because of the forced response, and predictions of the earliest possible ice-free conditions that could occur over a decade earlier because of internal variability[12]. Cumulative probabilities or the probability of ice-free conditions in a given year both provide opportunities to present both types of predictions (Fig. 3b–d), with the additional benefit of highlighting that ice-free predictions are always probabilistic. In addition, any communications must make it clear what thresholds and approaches are used, as demonstrated by SIA-based assessments leading to earlier ice-free conditions in comparison to SIE (ref. 69) (Fig. 3a). It also needs to be clearly communicated that currently published ice-free predictions focus on monthly averaged values, yet ice-free conditions will probably occur earlier when daily values are considered (in one model, 4 years earlier on average). Further projections using daily data are needed to assess whether such long daily–monthly offsets apply to other models.

Another important issue to consider is when the Arctic sea ice community will consider that an ice-free Arctic has been reached. Deciding on these criteria ahead of reaching ice free conditions is prudent given the various definitions as well as observational uncertainty in satellite-derived sea ice products (Fig. 1d). As such, it is possible that the 1 million km^2 ice-free threshold will be crossed in some SIA or SIE products under some definitions but not in others. Clarity on how this issue will be handled will facilitate communication around the occurrence of the first ice-free Arctic when it occurs.

Most predictions have focused on pan-Arctic ice-free conditions, yet this transition will occur regionally. Regional ice-free predictions, however, have been rare[75,81]. Efforts are needed to develop methods that better constrain regional sea ice projections and reduce their uncertainties. For example, how well existing model selection, weighting and recalibration perform for sea ice projections in different regions of the Arctic should be assessed. New methods might need to be developed to better constrain regional sea ice projections from climate models, always accounting for the irreducible internal variability uncertainty.

Given that climate model and statistical ice-free predictions are always probabilistic, it is also important to assess whether seasonal sea ice predictions have the skill needed to predict the first ice-free conditions at shorter lead times. Given that seasonal sea ice predictions often perform least well when the decline in a given year is far from that expected from the long-term trend, predictions of earliest ice-free conditions are potentially going to be challenging for current seasonal prediction systems[116]. Seasonal prediction experiments initialized with climate model conditions several months prior to a simulated early ice-free state could provide useful insights. Of course, these prediction assessments have their limitations, particularly associated with resolution and absent processes in large-scale climate models, but they might, nonetheless, provide useful insights into the skills of seasonal ice-free predictions.

To better constrain predictions of an ice-free Arctic, and of Arctic sea ice loss in general, dedicated intercomparisons of different model selection, weighting and recalibration methods are required. Currently, too many parameters (models, ensemble members, emission scenarios and ice-free definitions) differ to be able to identify the impact of an individual approach. Furthermore, defining best practice for skilfully reducing sea ice projection uncertainty would be very valuable, including deciding on the best set of metrics to base such methods on to improve projection accuracy and reduce projection uncertainty. Considering sea ice thickness[71] and ocean heat fluxes[98] as selection criteria should be part of that discussion. Additionally, biases in models should be used as an opportunity to better understand the real world[117]. For example, by analysing what drives features not seen in models but present in observations, progress can be made on improving models.

Finally, there is an urgent need to gain a better understanding of the impacts of an ice-free Arctic and the processes that could lead to an early ice-free Arctic, especially drivers of internal variability that contribute to ensemble spread. Such research could provide answers as to what is or what is not predictable, regionally and in the pan-Arctic mean. In terms of impacts, priorities should be given to understand ice-free effects on marine ecosystems, the global energy budget, wave height and coastal erosion. In particular, understanding the nuances of the impacts of occasional daily ice-free conditions versus frequent monthly ice-free conditions versus ice-free conditions that occur for several months a year is needed to assess the true impact of what the transition of the Arctic sea ice cover into its new seasonal sea ice regime means in a warming world.

Data availability

The CMIP6 sea ice area data is the same as analysed in ref. 10. The underlying SIC data, also used for the spatial plot (Fig. 5), is available on the Earth System Grid Federation (ESGF, https://esgf-node.llnl.gov/search/cmip6/). The data for the CESM2-LE (ref. 112) is available at https://www.cesm.ucar.edu/projects/cvdp-le/data-repository. The data for the CLIVAR Large Ensemble Archive[38] is available at https://www.earthsystemgrid.org/dataset/ucar.cgd.ccsm4.CLIVAR_LE.html.

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References

1. Notz, D. & Stroeve, J. Observed Arctic sea-ice loss directly follows anthropogenic CO_2 emission. *Science* **354**, 747–750 (2016).
2. Cavalieri, D. J., Parkinson, C. L., Gloersen, P., Comiso, J. C. & Zwally, H. J. Deriving long-term time series of sea ice cover from satellite passive-microwave multisensor data sets. *J. Geophys. Res.* **104**, 15803–15814 (1999).
3. Kwok, R. & Rothrock, D. A. Decline in Arctic sea ice thickness from submarine and ICESat records: 1958–2008. *Geophys. Res. Lett.* **36**, L15501 (2009).
4. Kacimi, S. & Kwok, R. Arctic snow depth, ice thickness, and volume from ICESat-2 and CryoSat-2: 2018–2021. *Geophys. Res. Lett.* **49**, e2021GL097448 (2022).
5. Stroeve, J. & Notz, D. Changing state of Arctic sea ice across all seasons. *Environ. Res. Lett.* **13**, 103001 (2018).
6. Meier, W., Fetterer, F., Windnagel, A. K. & Stewart, J. S. Climate data record of passive microwave sea ice concentration, version 4. *National Snow and Ice Data Center* https://nsidc.org/data/G02202/versions/4 (2021).
7. England, M., Jahn, A. & Polvani, L. Nonuniform contribution of internal variability to recent Arctic sea ice loss. *J. Clim.* **32**, 4039–4053 (2019).
8. Rantanen, M. et al. The Arctic has warmed nearly four times faster than the globe since 1979. *Commun. Earth Environ.* **3**, 168 (2022).
9. Parkinson, C. L. & Kellogg, W. Arctic sea ice decay simulated for a CO_2-induced temperature rise. *Clim. Change* **2**, 149–162 (1979).
10. Notz, D. & SIMIP Community. Arctic sea ice in CMIP6. *Geophys. Res. Lett.* **47**, e2019GL086749 (2020).
11. Notz, D. How well must climate models agree with observations? *Phil. Trans. R. Soc. A* **373**, 20140164 (2015).
12. Jahn, A., Kay, J., Holland, M. & Hall, D. How predictable is the timing of a summer ice-free Arctic? *Geophys. Res. Lett.* **43**, 9113–9120 (2016).
13. Knutti, R. et al. A climate model projection weighting scheme accounting for performance and interdependence. *Geophys. Res. Lett.* **44**, 1909–1918 (2017).
14. Massonnet, F. et al. Constraining projections of summer Arctic sea ice. *Cryosphere* **6**, 1383–1394 (2012).
15. Newton, R. et al. White Arctic vs. blue Arctic: a case study of diverging stakeholder responses to environmental change. *Earths Future* **4**, 396–405 (2016).
16. Polyak, L. et al. History of sea ice in the Arctic. *Quat. Sci. Rev.* **29**, 1757–1778 (2010).
17. Pistone, K., Eisenman, I. & Ramanathan, V. Observational determination of albedo decrease caused by vanishing Arctic sea ice. *Proc. Natl Acad. Sci. USA* **111**, 3322–3326 (2014).
18. Pistone, K., Eisenman, I. & Ramanathan, V. Radiative heating of an ice-free Arctic Ocean. *Geophys. Res. Lett.* **46**, 7474–7480 (2019).

19. Holland, M. & Bitz, C. Polar amplification of climate change in coupled models. *Clim. Dyn.* **21**, 221–232 (2003).
20. Screen, J. & Simmonds, I. The central role of diminishing sea ice in recent Arctic temperature amplification. *Nature* **464**, 1334–1337 (2010).
21. Dai, A., Luo, D., Song, M. & Liu, J. Arctic amplification is caused by sea-ice loss under increasing CO_2. *Nat. Commun.* **10**, 121 (2019).
22. Jenkins, M. & Dai, A. The impact of sea-ice loss on Arctic climate feedbacks and their role for Arctic amplification. *Geophys. Res. Lett.* **48**, e2021GL094599 (2021).
23. Casas-Prat, M. & Wang, X. Sea ice retreat contributes to projected increases in extreme Arctic Ocean surface waves. *Geophys. Res. Lett.* **47**, e2020GL088100 (2020).
24. Waseda, T. et al. Correlated increase of high ocean waves and winds in the ice-free waters of the Arctic Ocean. *Sci. Rep.* **8**, 4489 (2018).
25. Li, J., Ma, Y., Liu, Q., Zhang, W. & Guan, C. Growth of wave height with retreating ice cover in the Arctic. *Cold Reg. Sci. Technol.* **164**, 102790 (2019).
26. Overeem, I. et al. Sea ice loss enhances wave action at the Arctic coast. *Geophys. Res. Lett.* https://doi.org/10.1029/2011GL048681 (2011).
27. Nielsen, D., Pieper, P. & Barkhordarian, A. Increase in Arctic coastal erosion and its sensitivity to warming in the twenty-first century. *Nat. Clim. Change* **12**, 263–270 (2022).
28. Irrgang, A. M. et al. Drivers, dynamics and impacts of changing Arctic coasts. *Nat. Rev. Earth Environ.* **3**, 39–54 (2022).
29. Learmonth, J. A. et al. Potential effects of climate change on marine mammals. *Oceanogr. Mar. Biol.* **44**, 431 (2006).
30. Regehr, E. V., Lunn, N. J., Amstrup, S. C. & Stirling, I. Effects of earlier sea-ice breakup on survival and population size of polar bears in western Hudson Bay. *J. Wildl. Manag.* **71**, 2673–2683 (2007).
31. Laidre, K. L. et al. Quantifying the sensitivity of Arctic marine mammals to climate-induced habitat change. *Ecol. Appl.* **18**, S97–S125 (2008).
32. Renaut, S., Devred, E. & Babin, M. Northward expansion and intensification of phytoplankton growth during the early ice-free season in Arctic. *Geophys. Res. Lett.* **45**, 10,590–10,598 (2018).
33. Hollowed, A. B., Planque, B. & Loeng, H. Potential movement of fish and shellfish stocks from the sub-Arctic to the Arctic Ocean. *Fish. Oceanogr.* **22**, 355–370 (2013).
34. Ingvaldsen, R. B. et al. Physical manifestations and ecological implications of Arctic Atlantification. *Nat. Rev. Earth Environ.* **2**, 874–889 (2021).
35. Melia, N., Haines, K. & Hawkins, E. Sea ice decline and 21st century trans-Arctic shipping routes. *Geophys. Res. Lett.* **43**, 9720–9728 (2016).
36. Schiermeier, Q. The great Arctic oil race begins. *Nature* **482**, 13–14 (2012).
37. Eyring, V. et al. Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geosci. Model Dev.* **9**, 1937–1958 (2016).
38. Deser, C. et al. Insights from Earth system model initial-condition large ensembles and future prospects. *Nat. Clim. Change* **10**, 277–286 (2020).
39. Mewes, D. & Jacobi, C. Heat transport pathways into the Arctic and their connections to surface air temperatures. *Atmos. Chem. Phys.* **19**, 3927–3937 (2019).
40. Hahn, L. C., Armour, K. C., Battisti, D. S., Donohoe, A. & Fajber, R. Seasonal changes in atmospheric heat transport to the Arctic under increased CO_2. *Geophys. Res. Lett.* **50**, e2023GL105156 (2023).
41. Goosse, H. et al. Quantifying climate feedbacks in polar regions. *Nat. Commun.* **9**, 1919 (2018).
42. Kay, J. E. et al. Exposing global cloud biases in the Community Atmosphere Model (CAM) using satellite observations and their corresponding instrument simulators. *J. Clim.* **25**, 5190–5207 (2012).
43. Pithan, F. & Mauritsen, T. Arctic amplification dominated by temperature feedbacks in contemporary climate models. *Nat. Geosci.* **7**, 181–184 (2014).
44. Hahn, L. C., Armour, K. C., Zelinka, M. D., Bitz, C. M. & Donohoe, A. Contributions to polar amplification in CMIP5 and CMIP6 models. *Front. Earth Sci.* https://doi.org/10.3389/feart.2021.710036 (2021).
45. Bitz, C. M. & Roe, G. H. A mechanism for the high rate of sea ice thinning in the Arctic Ocean. *J. Clim.* **17**, 3623–3632 (2004).
46. Massonnet, F. et al. Arctic sea-ice change tied to its mean state through thermodynamic processes. *Nat. Clim. Change* **8**, 599–603 (2018).
47. Holland, M. M. & Landrum, L. The emergence and transient nature of Arctic amplification in coupled climate models. *Front. Earth Sci.* **9**, 719024 (2021).
48. Wang, M. & Overland, J. E. A sea ice free summer Arctic within 30 years? *Geophys. Res. Lett.* https://doi.org/10.1029/2009GL037820 (2009).
49. Notz, D. & Marotzke, J. Observations reveal external driver for Arctic sea-ice retreat. *Geophys. Res. Lett.* https://doi.org/10.1029/2012GL051094 (2012).
50. Kay, J. E., Holland, M. M. & Jahn, A. Inter-annual to multi-decadal Arctic sea ice extent trends in a warming world. *Geophys. Res. Let.* https://doi.org/10.1029/2011GL048008 (2011).
51. Mueller, B., Gillett, N., Monahan, A. & Zwiers, F. Attribution of Arctic sea ice decline from 1953 to 2012 to influences from natural, greenhouse gas, and anthropogenic aerosol forcing. *J. Clim.* **31**, 7771–7787 (2018).
52. Polvani, L. et al. Substantial twentieth-century Arctic warming caused by ozone-depleting substances. *Nat. Clim. Change* **10**, 130–133 (2020).
53. England, M. R. & Polvani, L. M. The Montreal Protocol is delaying the occurrence of the first ice-free Arctic summer. *Proc. Natl Acad. Sci. USA* **120**, e2211432120 (2023).
54. Mahlstein, I. & Knutti, R. September Arctic sea ice predicted to disappear near 2 °C global warming above present. *Geophys. Res. Lett.* https://doi.org/10.1029/2011JD016709 (2012).
55. Stroeve, J. & Notz, D. Insights on past and future sea-ice evolution from combining observations and models. *Glob. Planet. Change* **135**, 119–132 (2015).
56. Ding, Q. et al. Influence of high-latitude atmospheric circulation changes on summertime Arctic sea ice. *Nat. Clim. Change* **7**, 289–295 (2017).
57. Roach, L. & Blanchard-Wrigglesworth, E. Observed winds crucial for Arctic sea ice loss. *Geophys. Res. Lett.* **49**, e2022GL097884 (2022).
58. Olonscheck, D., Mauritsen, T. & Notz, D. Arctic sea-ice variability is primarily driven by atmospheric temperature fluctuations. *Nat. Geosci.* **12**, 430–434 (2019).
59. Polyakov, I. V. et al. Fluctuating Atlantic inflows modulate Arctic Atlantification. *Science* **381**, 972–979 (2023).
60. Holland, M. M., Bitz, C. M. & Tremblay, B. Future abrupt reductions in the summer Arctic sea ice. *Geophys. Res. Lett.* https://doi.org/10.1029/2006GL028024 (2006).
61. Goosse, H., Arzel, O., Bitz, C. M., de Montety, A. & Vancoppenolle, M. Increased variability of the Arctic summer ice extent in a warmer climate. *Geophys. Res. Lett.* https://doi.org/10.1029/2009GL040546 (2009).
62. Mioduszewski, J. R., Vavrus, S., Wang, M., Holland, M. & Landrum, L. Past and future interannual variability in Arctic sea ice in coupled climate models. *Cryosphere* **13**, 113–124 (2019).
63. Auclair, G. & Tremblay, L. B. The role of ocean heat transport in rapid sea ice declines in the Community Earth System Model Large Ensemble. *J. Geophys. Res. Oceans* **123**, 8941–8957 (2018).
64. Döscher, R. & Koenigk, T. Arctic rapid sea ice loss events in regional coupled climate scenario experiments. *Ocean Sci.* **9**, 217–248 (2013).
65. Paquin, J.-P., Döscher, R., Sushama, L. & Koenigk, T. Causes and consequences of mid-21st-century rapid ice loss events simulated by the Rossby Centre regional atmosphere-ocean model. *Tellus A Dyn. Meteorol. Oceanogr.* https://doi.org/10.3402/tellusa.v65i0.19110 (2013).
66. Vavrus, S., Holland, M. & Bailey, D. Changes in Arctic clouds during intervals of rapid sea ice loss. *Clim. Dyn.* **36**, 1475–1489 (2011).
67. Boe, J., Hall, A. & Qu, X. September sea-ice cover in the Arctic Ocean projected to vanish by 2100. *Nat. Geosci.* **2**, 341–343 (2009).
68. Pfirman, S., Haxby, W. F., Colony, R. & Rigor, I. Variability in the Arctic sea ice drift. *Geophys. Res. Lett.* https://doi.org/10.1029/2004GL020063 (2004).
69. DeRepentigny, P., Jahn, A., Holland, M. M. & Smith, A. Arctic sea ice in two configurations of the CESM2 during the 20th and 21st centuries. *J. Geophys. Res. Oceans* **125**, e2020JC016133 (2020).
70. Wang, B., Zhou, X., Ding, Q. & Liu, J. Increasing confidence in projecting the Arctic ice-free year with emergent constraints. *Environ. Res. Lett.* https://doi.org/10.1088/1748-9326/ac0b17 (2021).
71. Zhou, X., Wang, B. & Huang, F. Evaluating sea ice thickness simulation is critical for projecting a summer ice-free Arctic Ocean. *Environ. Res. Lett.* **17**, 114033 (2022).
72. Landrum, L. & Holland, M. Extremes become routine in an emerging new Arctic. *Nat. Clim. Change* **10**, 1108–1115 (2020).
73. Thackeray, C. & Hall, A. An emergent constraint on future Arctic sea-ice albedo feedback. *Nat. Clim. Change* **9**, 972–978 (2019).
74. Snape, T. J. & Forster, P. M. Decline of Arctic sea ice: evaluation and weighting of CMIP5 projections. *J. Geophys. Res. Atmos.* **119**, 546–554 (2014).
75. Laliberté, F., Howell, S. E. L. & Kushner, P. J. Regional variability of a projected sea ice-free Arctic during the summer months. *Geophys. Res. Lett.* **43**, 256–263 (2016).
76. Jahn, A. Reduced probability of ice-free summers for 1.5 °C compared to 2 °C warming. *Nat. Clim. Change* **8**, 409–413 (2018).
77. Bonan, D. B., Schneider, T., Eisenman, I. & Wills, R. C. J. Constraining the date of a seasonally ice-free Arctic using a simple model. *Geophys. Res. Lett.* **48**, e2021GL094309 (2021).
78. Kim, Y., Min, S., Gillett, N., Notz, D. & Malinina, E. Observationally-constrained projections of an ice-free Arctic even under a low emission scenario. *Nat. Commun.* **14**, 3139 (2023).
79. Screen, J. A. & Williamson, D. Ice-free Arctic at 1.5 °C? *Nat. Clim. Change* **7**, 230–231 (2017).
80. Sigmond, M., Fyfe, J. C. & Swart, N. C. Ice-free Arctic projections under the Paris Agreement. *Nat. Clim. Change* **8**, 404–408 (2018).
81. Arthun, M., Onarheim, I. H., Dörr, J. & Eldevik, T. The seasonal and regional transition to an ice-free Arctic. *Geophys. Res. Lett.* **48**, e2020GL090825 (2021).
82. Ridley, J. K. & Blockley, E. W. Brief communication: solar radiation management not as effective as CO_2 mitigation for Arctic sea ice loss in hitting the 1.5 and 2 °C COP climate targets. *Cryosphere* **12**, 3355–3360 (2018).
83. Stroeve, J. C. et al. Trends in Arctic sea ice extent from CMIP5, CMIP3 and observations. *Geophys. Res. Lett.* https://doi.org/10.1029/2012GL052676 (2012).
84. Notz, D. & Stroeve, J. The trajectory towards a seasonally ice-free Arctic Ocean. *Curr. Clim. Change Rep.* **4**, 407–416 (2018).
85. Niederdrenk, A. L. & Notz, D. Arctic sea ice in a 1.5 °C warmer world. *Geophys. Res. Lett.* **45**, 1963–1971 (2018).
86. Diebold, F. X. & Rudebusch, G. D. Probability assessments of an ice-free Arctic: comparing statistical and climate model projections. *J. Econom.* **231**, 520–534 (2022).
87. Hawkins, E. & Sutton, R. The potential to narrow uncertainty in regional climate predictions. *Bull. Amer. Meteor. Soc.* **90**, 1095–1107 (2009).
88. Lorenz, E. N. Deterministic nonperiodic flow. *J. Atmos. Sci.* **20**, 130–141 (1963).
89. Holland, M. & Hunke, E. A review of Arctic sea ice climate predictability in large-scale earth system models. *Oceanography* **35**, 20–27 (2022).
90. Screen, J. A. & Deser, C. Pacific Ocean variability influences the time of emergence of a seasonally ice-free Arctic Ocean. *Geophys. Res. Lett.* **46**, 2222–2231 (2019).

91. Blanchard-Wrigglesworth, E., Bitz, C. M. & Holland, M. M. Influence of initial conditions and climate forcing on predicting Arctic sea ice. *Geophys. Res. Lett*. https://doi.org/10.1029/2011GL048807 (2011).
92. Senftleben, D., Lauer, A. & Karpechko, A. Constraining uncertainties in CMIP5 projections of September Arctic sea ice extent with observations. *J. Clim.* **33**, 1487–1503 (2020).
93. Meier, W. N. & Stewart, J. S. Assessing uncertainties in sea ice extent climate indicators. *Environ. Res. Lett.* **14**, 035005 (2019).
94. Swart, N. C., Fyfe, J. C., Hawkins, E., Kay, J. E. & Jahn, A. Influence of internal variability on Arctic sea-ice trends. *Nat. Clim. Change* **5**, 86â89 (2015).
95. Maslowski, W., Kinney, J. C., Higgins, M. & Roberts, A. The future of Arctic sea ice. *Annu. Rev. Earth Planet. Sci.* **40**, 625–654 (2012).
96. Wang, M. & Overland, J. E. A sea ice free summer Arctic within 30 years: an update from CMIP5 models. *Geophys. Res. Lett.* https://doi.org/10.1029/2012GL052868 (2012).
97. Liu, J., Curry, J. A., Wang, H. & Horton, R. M. Impact of declining Arctic sea ice on winter snowfall. *Proc. Natl Acad. Sci. USA* https://doi.org/10.1073/pnas.1114910109 (2012).
98. Docquier, D. & Koenigk, T. Observation-based selection of climate models projects Arctic ice-free summers around 2035. *Commun. Earth Environ.* **2**, 144 (2021).
99. Topal, D. & Ding, Q. Atmospheric circulation-constrained model sensitivity recalibrates Arctic climate projections. *Nat. Clim. Change* **13**, 710–718 (2023).
100. Khosravi, N. et al. The Arctic Ocean in CMIP6 models: biases and projected changes in temperature and salinity. *Earths Future* **10**, e2021EF002282 (2022).
101. Muilwijk, M. et al. Divergence in climate model projections of future Arctic Atlantification. *J. Clim.* **36**, 1727–1748 (2023).
102. Heuzè, C., Zanowski, H., Karam, S. & Muilwijk, M. The deep Arctic Ocean and Fram Strait in CMIP6 models. *J. Clim.* **36**, 2551–2584 (2023).
103. O'Neill, B. C. et al. The Scenario Model Intercomparison Project (ScenarioMIP) for CMIP6. *Geosci. Model Dev.* **9**, 3461–3482 (2016).
104. Bonan, D. B., Lehner, F. & Holland, M. M. Partitioning uncertainty in projections of Arctic sea ice. *Environ. Res. Lett.* **16**, 044002 (2021).
105. Lindsay, R. W., Zhang, J., Schweiger, A., Steele, M. & Stern, H. Arctic sea ice retreat in 2007 follows thinning trend. *J. Clim.* **22**, 165–176 (2009).
106. Parkinson, C. L. & Comiso, J. C. On the 2012 record low Arctic sea ice cover: combined impact of preconditioning and an August storm. *Geophys. Res. Lett.* **40**, 1356–1361 (2013).
107. Sanderson, B. et al. Community climate simulations to assess avoided impacts in 1.5 °C and 2 °C futures. *Earth Syst. Dyn.* **8**, 827–847 (2017).
108. Screen, J. Arctic sea ice at 1.5 and 2 °C. *Nat. Clim. Change* **8**, 362–363 (2018).
109. Tietsche, S., Notz, D., Jungclaus, J. H. & Marotzke, J. Recovery mechanisms of Arctic summer sea ice. *Geophys. Res. Lett.* https://doi.org/10.1029/2010GL045698 (2011).
110. Armour, K. C., Eisenman, I., Blanchard-Wrigglesworth, E., McCusker, K. E. & Bitz, C. M. The reversibility of sea ice loss in a state of the art climate model. *Geophys. Res. Lett*. https://doi.org/10.1029/2011GL048739 (2011).
111. Li, C., Notz, D., Tietsche, S. & Marotzke, J. The transient versus the equilibrium response of sea ice to global warming. *J. Clim.* **26**, 5624–5636 (2013).
112. Rodgers, K. B. et al. Ubiquity of human-induced changes in climate variability. *Earth Syst. Dyn.* **12**, 1393–1411 (2021).
113. Lebrun, M., Vancoppenolle, M., Madec, G. & Massonnet, F. Arctic sea-ice-free season projected to extend into autumn. *Cryosphere* **13**, 79–96 (2019).
114. Tebaldi, C. et al. Climate model projections from the Scenario Model Intercomparison Project (ScenarioMIP) of CMIP6. *Earth Syst. Dyn.* **12**, 253–293 (2021).
115. Jahn, A. & Holland, M. M. Implications of Arctic sea ice changes for North Atlantic deep convection and the meridional overturning circulation in CCSM4-CMIP5 simulations. *Geophys. Res. Let.* **40**, 1206–1211 (2013).
116. Hamilton, L. & Stroeve, J. 400 predictions: the SEARCH Sea Ice Outlook 2008–2015. *Polar Geogr.* **39**, 274–287 (2016).
117. Ding, Q. et al. Fingerprints of internal drivers of Arctic sea ice loss in observations and model simulations. *Nat. Geosci.* **12**, 28–33 (2019).
118. Stroeve, J., Holland, M. M., Meier, W., Scambos, T. & Serreze, M. Arctic sea ice decline: faster than forecast. *Geophys. Res. Lett*. https://doi.org/10.1029/2007GL029703 (2007).
119. Liu, J., Song, M., Horton, R. M. & Hu, Y. Reducing spread in climate model projections of a September ice-free Arctic. *Proc. Natl Acad. Sci. USA* **110**, 12571–12576 (2013).
120. Rosenblum, E. & Eisenman, I. Faster Arctic sea ice retreat in CMIP5 than in CMIP3 due to volcanoes. *J. Clim.* **29**, 9179–9188 (2016).
121. Dörr, J., Notz, D. & Kern, S. UHH sea ice area product. *Universität Hamburg* https://doi.org/10.25592/uhhfdm.8559 (2021).
122. Comiso, J. *SSM/I Concentrations Using the Bootstrap Algorithm* (NASA, 1995).
123. Cavalieri, D., Gloersen, P. & Campbell, W. Determination of sea ice parameters with the Nimbus 7 SMMR. *J. Geophys. Res.* **89**, 5355–5369 (1984).
124. Krylov, A. et al. A shift in heavy and clay mineral provenance indicates a middle Miocene onset of a perennial sea ice cover in the Arctic Ocean. *Paleoceanogr. Paleoclimatol.* https://doi.org/10.1029/2007PA001497 (2008).
125. Darby, D. Arctic perennial ice cover over the last 14 million years. *Paleoceanogr. Paleoclimatol.* https://doi.org/10.1029/2007PA001479 (2008).
126. Miller, G. et al. Temperature and precipitation history of the Arctic. *Quat. Sci. Rev.* **29**, 1679–1715 (2010).
127. Tarduno, J. A. et al. Evidence for extreme climatic warmth from late Cretaceous Arctic vertebrates. *Science* **282**, 2241–2243 (1998).
128. Jenkyns, H., Forster, A., Schouten, S. & Damsté, J. S. S. High temperatures in the late Cretaceous Arctic Ocean. *Nature* **432**, 888–892 (2004).
129. Nathorst, A. G. Ueber die reste eines Brotfruchtbaums *Artocarpus dicksonii* n. sp., aus den cenomanen Kreideablagerungen Grönlands. *Kongl. Svenska Vetenskaps-Akad. Hand.* **24**, 2–9 (1890).
130. Stein, R. et al. Evidence for ice-free summers in the late Miocene central Arctic Ocean. *Nat. Commun.* **7**, 11148 (2016).
131. Nøgaard-Pedersen, N., Mikkelsen, N. & Kristoffersen, Y. Arctic Ocean record of last two glacial-interglacial cycles off North Greenland/Ellesmere Island — implications for glacial history. *Mar. Geol.* **244**, 93–108 (2007).
132. Nørgaard-Pedersen, N., Mikkelsen, N., Lassen, S. J., Kristoffersen, Y. & Sheldon, E. Reduced sea ice concentrations in the Arctic Ocean during the last interglacial period revealed by sediment cores off Northern Greenland. *Paleoceanogr. Paleoclimatol.* **22**, PA1218 (2007).
133. Adler, R. E. et al. Sediment record from the western Arctic Ocean with an improved late quaternary age resolution: HOTRAX core HLY0503-8JPC, Mendeleev Ridge. *Glob. Planet. Change* **68**, 18–29 (2009).
134. Sime, L. C., Sivankutty, R., Vallet-Malmierca, I., de Boer, A. M. & Sicard, M. Summer surface air temperature proxies point to near-sea-ice-free conditions in the Arctic at 127 ka. *Clim. Past* **19**, 883–900 (2023).
135. Vermassen, F. et al. A seasonally ice-free Arctic Ocean during the last interglacial. *Nat. Geosci.* **16**, 723–729 (2023).
136. Lozhkin, A. V. & Anderson, P. M. The last interglaciation in northeast Siberia. *Quat. Res.* **43**, 147–158 (1995).
137. Tremblay, L. B., Schmidt, G. A., Pfirman, S., Newton, R. & DeRepentigny, P. Is ice-rafted sediment in a North Pole marine record evidence for perennial sea-ice cover? *Phil. Trans. Roy. Soc. A* **373**, 2052 (2015).
138. de Vernal, A. et al. Natural variability of the Arctic Ocean sea ice during the present interglacial. *Proc. Natl Acad. Sci. USA* **117**, 26069–26075 (2020).
139. Jakobsson, M., Long, A., Ingoĺfsson, O., Kjær, K. H. & Spielhagen, R. F. New insights on Arctic quaternary climate variability from palaeo-records and numerical modelling. *Quat. Sci. Rev.* **29**, 3349–3358 (2010).
140. Pfirman, S., Fowler, C., Tremblay, B. & Newton, R. The last Arctic sea ice refuge. *Circle* **4**, 6–8 (2009).
141. Newton, R., Pfirman, S., Tremblay, L. B. & DeRepentigny, P. Defining the "ice shed" of the Arctic Ocean's last ice area and its future evolution. *Earths Future* **9**, e2021EF001988 (2021).

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Author contributions
A.J. decided on the overall scope of the article, wrote the majority of the article, and did all data analyses for the figures in the main article. M.M.H. and J.E.K. contributed to the writing of the manuscript, provided input on the article scope and figures, and edited the manuscript. M.M.H. also performed data analysis for supplementary figures and created one of the supplementary figures.

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The authors declare no competing interests.

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