Surprising, but not unexpected, multi-decadal pause in Arctic sea ice loss

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Abstract

Over the past two decades, Arctic sea ice loss has slowed considerably, with no statistically significant decline in September sea ice area since 2005. This pause is robust across observational datasets, metrics, and seasons. Large-ensemble CMIP5 and CMIP6 simulations reveal that such periods with no sea ice decline under increasing greenhouse gas emissions are not unusual. Analysis of ensemble members that simulate analogues of the observed pause indicates that the current slowdown could plausibly persist another five to ten years. The modelling evidence suggests that internal variability has substantially offset anthropogenically forced sea ice loss in recent decades, although possible contributions from changes in the forced response remain uncertain. Overall, this observed pause in Arctic sea ice decline is consistent with simulated internal variability superimposed on the long term trend according to the bulk of the climate modelling evidence.

Surprising, but not unexpected, multi-decadal pause in Arctic sea ice loss

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Key Points:

- The loss of Arctic sea ice cover has undergone a pronounced slowdown over the past two decades, across all months of the year.
- Rather than being an unexpected rare event, comprehensive climate models from CMIP5 and CMIP6 simulate such pauses relatively frequently.
- According to these climate model simulations, this pause in the loss of Arctic sea ice could plausibly continue for the next 5-10 years.

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Abstract

Over the past two decades, Arctic sea ice loss has slowed considerably, with no statistically significant decline in September sea ice area since 2005. This pause is robust across observational datasets, metrics, and seasons. Large-ensemble CMIP5 and CMIP6 simulations reveal that such periods with no sea ice decline under increasing greenhouse gas emissions are not unusual. Analysis of ensemble members that simulate analogues of the observed pause indicates that the current slowdown could plausibly persist another five to ten years. The modelling evidence suggests that internal variability has substantially offset anthropogenically forced sea ice loss in recent decades, although possible contributions from changes in the forced response remain uncertain. Overall, this observed pause in Arctic sea ice decline is consistent with simulated internal variability superimposed on the long term trend according to the bulk of the climate modelling evidence.

Plain Language Summary

Over the last 20 years, the decline of Arctic sea ice has slowed down substantially. Climate models (from CMIP5 and CMIP6) show that pauses in sea ice loss across multiple decades can happen, even as greenhouse gas emissions continue to rise. When we compare the current slowdown to similar pauses in model simulations, we see that this “hiatus” could plausibly continue for another five to ten years. Most of the evidence from these climate models suggests that natural climate variations have played a large part in slowing the human-driven loss of sea ice. However, it is not entirely certain whether changes in the human influence on climate (the “forced response”) have also contributed. Overall, while it may sound surprising that Arctic sea ice loss has slowed down even as global temperatures hit record highs, the climate modelling evidence suggests we should expect periods like this to occur somewhat frequently.

1 Introduction

The loss of Arctic sea ice over the past half century is one of the most clear and well-known indicators of human-induced climate change (IPCC, 2021; Copernicus, 2024). September sea ice area has nearly halved since the beginning of the satellite era in 1979 (Fetterer et al., 2017; Stroeve & Notz, 2018), and during the same period, estimated Arctic sea ice volume has decreased by over 10,000 km^3 (Kwok, 2018). Record-breaking summer sea ice minimums in 2007 (Stroeve et al., 2011) and 2012 (Parkinson & Comiso, 2013; J. Zhang et al., 2013) fuelled predictions, which with hindsight look overly alarmist, that the Arctic would experience its first ice-free summer before 2020 (Maslowski et al., 2012; Wadhams, 2016). Adding to this, the Arctic has been warming up to four times faster than the global average (Rantanen et al., 2022). It has been further proposed that global warming might be accelerating, culminating in record breaking warmth in recent years (Samset et al., 2023; Hansen et al., 2025; Merchant et al., 2025). As Arctic sea ice cover is strongly tied to global temperatures (Notz & Stroeve, 2016), there would be little expectation of a multi-decadal *slowdown* in Arctic sea ice loss. And yet, as we will show, such a slowdown has been occurring in the last two decades.

Recall that, over the past century, periods of increasing anthropogenic greenhouse emissions without sustained sea ice loss - the mid-20th century (Walsh et al., 2017) - have already occurred. From the 1940s to the 1970s Arctic sea ice cover *expanded* (Gagne et al., 2017), with the largest increases in the Chukchi, East Siberian, Laptev, Kara and Barents Seas. However, anthropogenic forcing in the mid-20th century was very different compared to the one of the past two decades. Industrial aerosol emissions from Europe and North America contributed substantially to the positive multi-decadal trend in Arctic sea ice area and associated Arctic cooling in the mid-20th century (Fyfe et al., 2013; Nafaji et al., 2015; Gagne et al., 2017; England et al., 2021); but these aerosol sources are far smaller today (Szopa et al., 2013; Lund et al., 2019). However, when anthropogenic aerosols are being discussed in the context of the recent past, it is with regards to the phase out of aerosol emissions from ship tracks which have potentially contributed to enhanced global warming since 2020 (Manshausen et al., 2022; Yoshioka et al., 2024). In fact, Yoshioka et al. (2024) find that the simulated warming response to these reduced sulphur emissions is largest in the Arctic. So, the lessons of the past may not be a reliable guide for understanding current trends.

It is important to appreciate that the observed trend in Arctic sea ice cover over a given period is composed of a contribution caused by anthropogenic emissions, denoted the forced response, and a contribution from unforced fluctuations associated with internal climate variability (England et al., 2019; England, 2021; Dörr et al., 2023; Shen et al., 2024). Anthropogenically-forced changes which may contribute to a reduction in Arctic sea ice loss over the past two decades include a forced slowdown in the Atlantic Meridional Overturning Circulation (Lee & Liu, 2023), and changes in the emissions from biomass burning, both in the magnitude (Blanchard-Wrigglesworth et al., 2025), and the variability (DeRepentigny et al., 2022). One would imagine, however, that the aforementioned reduction of sulphur emission from shiptracks (Yoshioka et al., 2024) would lead to an acceleration rather than a deceleration of sea ice loss since 2020. Alternatively modes of climate variability which act on multi-decadal timescales, such as the Atlantic Multi-decadal Oscillation (Kerr, 2000; Deser & Phillips, 2021) and the Pacific Decadal Oscillation (Mantua & Hare, 2002), have an important imprint on Arctic sea ice. For example, variability emanating from the Pacific sector (Ding et al., 2018; Baxter et al., 2019) or Atlantic sector (Meehl et al., 2018) has been suggested to have substantially contributed to the rapid loss of Arctic sea ice during the 2000s (England et al., 2019). A number of recent studies, using different methods including standard optimal detection method (Shen et al., 2024), machine learning (Siew et al., 2024) and low-frequency component analysis (Dörr et al., 2023), conclude that internal variability is at least as important as anthropogenic forcing, perhaps more, for explaining the steep decline in that period. Needless to say, internal variability can damp sea ice loss trends as well as strengthen them. For instance, Yeager et al. (2015) correctly predicted a slowdown of winter Atlantic sector sea ice loss for the past decade based on predictability from oceanic conditions linked to the North Atlantic Oscillation.

In fact, it has been found in climate model simulations that internal climate variability can totally counteract the forced loss of Arctic sea ice, resulting in periods of simulated sea ice growth under increasing anthropogenic emissions. Kay et al. (2011) were among the first to demonstrate, in a single climate model, that positive trends in Arctic sea ice extent on multi-decadal timescales were possible until the middle of this century. They found, using a limited ensemble size of six members, that two members exhibited statistically insignificant trends in September for the period 1979-2005 due to a cancellation between the forced response and internal climate variability. Motivated by the as-of-then brief pause in September Arctic sea ice loss for the period 2007-2013, Swart et al. (2015) analyzed the CMIP5 archive and showed that seven-year pauses occurred frequently in model simulations, and concluded that such episodes are an expected feature of Arctic sea ice trajectory, even in a high emissions scenario. This study also demonstrated that pauses in sea ice loss on multi-decadal timescales remain plausible, and relatively frequent, over the coming century under a medium- or low-emissions scenario. Looking back from the vantage point of 2025, the model-based studies of Kay et al. (2011) and Swart et al. (2015) now appear remarkably prescient with regards to the plausibility of a sustained slowdown in Arctic sea ice loss.

In this paper we document the recent observed multi-decadal pause in Arctic sea ice loss and address the following questions:

1. How extensive and robust is this pause in Arctic sea ice loss?

2. Are comprehensive climate models able to capture this observed phenomenon, and if so how likely is it suggested to be?
3. How long could this observed pause plausibly persist for?
4. What is the role of anthropogenic forcing versus internal climate variability in contributing to the slow rate of sea ice loss?

2 Data and Methods

To investigate the evolution in Arctic sea ice cover, we utilise both the NSIDC (Fetterer et al., 2017) and the OSISAF (OSI-420, 2023) sea ice indices. Both of these are continually updated data records of the Arctic sea area and extent, for the period 1979 - present, derived from satellite measurements. We note that there are known systematic differences in the mean state between the two products (Meier & Stewart, 2019) but their interannual variations and multi-decadal trends have strong similarities (Figures 1a,b and S1). For understanding changes in the simulated Arctic sea ice volume we utilise the Pan-Arctic Ice Ocean Modeling and Assimilation System (PIOMAS) product (Schweiger et al., 2011).

To investigate the frequency and length of pauses in Arctic sea ice loss in comprehensive climate model simulations, we here analyze all available large ensemble simulations from the CMIP5 and CMIP6 archive. Any model with at least ten members is used, as summarised in Table S1. For the CMIP5 models, we use historical simulations which terminate at the year 2005, followed by the ScenarioMIP simulations with a range of Representative Concentration Pathways (RCPs). For the CMIP6 models, we use historical simulations up to the year 2014, followed by ScenarioMIP simulations with a range of Shared Socioeconomic Pathways (SSPs).

The main approach for analysing simulated changes in Arctic sea ice cover is to compute the linear trend for the twenty-year period 2005-2024 for each individual member available for each model, as motivated by the observed changes (Section 3.1). This gives a range between 10 and 100 members to examine the spread of simulated trends for each model and scenario. To check for robustness by looking over a large sample size, we also expand the overall time period by ten years each side (1995-2034), or shorter if the ensemble mean has transitioned to ice-free conditions before 2035, and then calculate all of the possible 20-year trends during this period; this, however, does not substantially alter the results. The main definition of slowdown used in this study is motivated by the observed 2005-2024 September sea ice area trends (> -0.29 million km^2/dec). We also use an alternative definition – trends which are not statistically significant at the 95% confidence level – to ensure that this specific observed threshold does not overly influence the results. This secondary definition contains information about the signal to noise ratio, and so is complementary to the trend threshold definition. However, we find that both definitions produce consistent results.

When we report multi-model averages, we do so by using a square-root weighting scheme to take account of the number of members in each ensemble (models with more members are weighted higher because the larger sample size will provide a more robust estimate of the probability of a slowdown occurring) and the number of scenarios (models with more scenarios are down-weighted because they are not independent of each other). Doing this ensures that models with multiple scenarios are treated as if they have more members of the same model scenario. The weighting for each model i and scenario j of a given selection, where the number of members for each model for a given scenario is n_{ij} and the number of scenarios for each model is given by s_i is calculated as:

$$w_{ij} = \frac{\sqrt{a_{ij}}/\sqrt{s_i}}{\sum_{i,j}[\sqrt{a_{ij}}/\sqrt{s_i}]} \qquad (1)$$

However, we emphasize that this weighting scheme does not substantially alter the conclusions compared to if all members were weighted equally (not shown).

3 Results

3.1 A robust and sustained pause in Arctic sea ice loss

We first investigate the recent observed trends in Arctic sea ice cover, focusing on the annual minimum, September. The trend of September Arctic sea ice area for the most recent two decades 2005-2024 is -0.30 and -0.29 million km^2 per decade according to the NSIDC and OSISAF sea ice indices respectively (Fig. 1a,b). The key point, we emphasize, is that these trends are not statistically significantly different from zero at a 95% confidence level. This is also seen in Figure 1c,d where 20-year trends are plotted versus the end year: note how trends ending in 2024 retreat inside the uncertainty envelope. According to the OSISAF record, the 2005-2024 trend is the slowest rate of sea ice area loss over any 20-year period since the start of the satellite record. For both datasets, this insignificant trend is approximately four-times smaller than the peak 20-year sea ice loss trend recorded (1993-2012). These results are robust to the choice of sea ice area or sea ice extent (Fig. S1). The slowdown in September sea ice loss mainly occurs in the Pacific and Eurasian sector, from the Beaufort Sea westward to the Barents Sea (not shown).

While sea ice loss in September is of particular interest because that month is the annual minimum, the current pause in Arctic sea ice loss is seen in every single month throughout the year, as shown in Figure 1e,f). This suggests that the underlying mechanism(s) must explain not just the summer trends (R. Zhang, 2015; Francis & Wu, 2020) or winter trends (Yeager et al., 2015), but sea ice trends throughout the entire year.

The same picture - indicating a severe slowdown in Arctic sea ice loss - also emerges when considering sea ice volume. The loss of Arctic sea ice volume has stalled for at least the past fifteen years (Fig. S2). For the period 2010-2024, the simulated annual mean Arctic sea ice volume has an approximately flat trend, decreasing by only 0.4 million km^3 per decade, a value that is 7-times smaller than the long-term simulated loss for the period 1979-2024 of 2.9 million km^3 per decade, and again is not statistically significant. This result, which is most evident in the Barents Sea (Onarheim et al., 2024), is consistent with a recent analysis suggesting a net build-up of sea ice volume since 2007 due to a decrease in ice export from the Arctic, in addition to the thinner ice cover exhibiting higher growth rates (J. Zhang, 2021).

Given the strong observational evidence for a sustained and pervasive pause in Arctic sea ice loss over the recent 15-20 years, highly robust to the choice of sea ice metric, observational product, and season, we are led to ask: is such a pause unexpected? To answer that question we turn to analyzing comprehensive climate model simulations. We seek to determine if they are able to capture pauses such as the observed one and, if so, to establish if such pauses are exceedingly rare or relatively frequent events.

3.2 Comprehensive climate models suggest 20-year pauses are not rare

To understand whether comprehensive climate models can simulate a multi-decadal pause of Arctic sea ice loss, we search through the CMIP5 and CMIP6 large ensemble archive to identify members which exhibit ice loss pauses. Consistent with previous studies (Kay et al., 2011; Swart et al., 2015; Lee & Liu, 2023), we find that nearly all models are able to simulate reductions in September Arctic sea ice area smaller than observed during the period 2005-2024. The two models which do not feature any such trends, UKESM1-0-LL and CanESM5-1, are both models with large climate sensitivities (Meehl et al., 2020), for which overly strong anthropogenically-forced sea ice loss does not allow for pauses such as the observed one.

Figure 2a shows the percentage of members with sea ice loss smaller than observed. The main result here is that the multi-model average suggests an approximately 20% chance of this pause in Arctic sea ice loss (Fig. 2a, column 1). However, we note a large spread

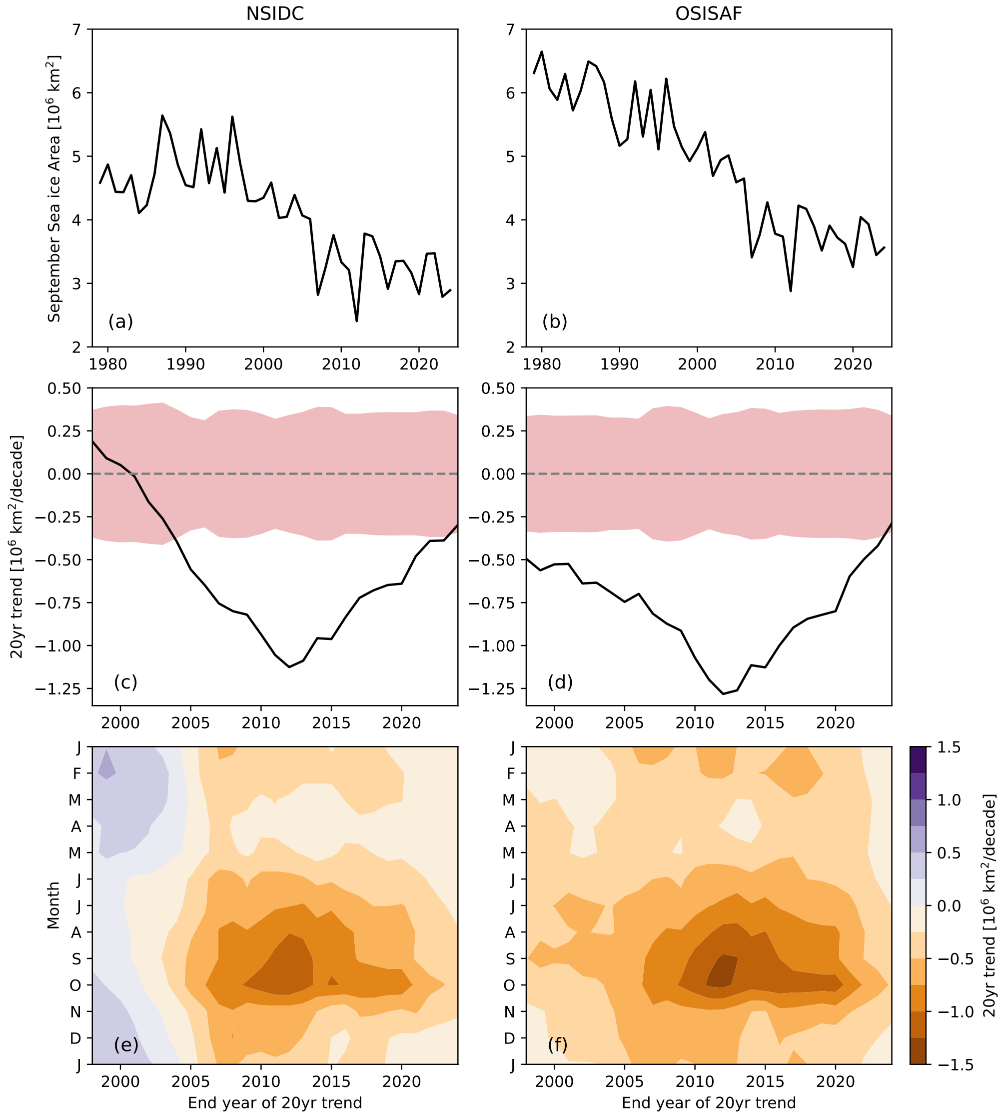

Figure 1. (a,b) Observed sea ice area [10^6 km^2] 1979-2024, (c,d) 20 year-trends of September sea ice area [10^6 km^2/decade] with varying end year from 1998 to 2024, in which the red shaded envelope shows the bounds inside which a linear trend is not statistically significant according to a t-test at 95% confidence and (e,f) the 20 year-trends of sea ice area with varying end years but for each month of the year. The left column (a,c,e) shows the NSIDC sea index (Fetterer et al., 2017) and the right column (b,d,f) shows the OSISAF sea ice index (OSI-420, 2023).

across the CMIP5 and CMIP6 models, with the probability of a smaller-than-observed 2005-2024 trend varying from 0% and approximately 50%. Interestingly, the spread across models for a given scenario is much larger than the spread across scenarios for a given model. This is perhaps unsurprising because the scenarios diverge from each other later than the 2020s (Notz & SIMIP Community, 2020), especially for the case of the CMIP6 forcing.

The central estimated value of approximately 20% doesn't change substantially if models are selected following the criteria from Notz and SIMIP Community (2020), or using models lying in the 66% range and 5-95% range estimates of the climate sensitivity (Sherwood et al., 2020), or using models according to their ability to simulate climatological sea ice conditions for the period 1979-1998 (Fig. 2a, column 2-4). Nor is the central estimate substantially impacted if we assess the probability of a non-statistically significant trend (Figure S3): this value is only slightly higher at approximately 25%. Therefore from the multi-model perspective, what we have observed in the Arctic over the past two decades is not a rare event, but rather one that should be expected to happen with reasonable frequency. This result is insensitive to how models are sub-selected, or to the metric of interest. This then raises the question of whether this pause in Arctic sea ice loss could continue and for how long.

3.3 The observed pause in sea ice loss could foreseeably continue for another decade

To investigate how much longer this current pause is likely to last into the future, we now examine those large ensemble members which do exhibit muted sea ice loss in the period from 2005-2024 (Fig. 2a), and quantify how long the simulated slowdowns persist in the future (Fig. 2b). In essence this produces the conditional probability estimate of the 20-year pause extending further for each model and scenario. The multi-model average suggests that pauses in September sea ice loss for the period 2005-2024 have a 1 in 2 chance of persisting for a further five years, and a 1 in 3 chance of persisting for a further ten years (note, however, the considerable intermodel spread of $\pm$ 25%). On average, higher emissions scenarios tend to show slightly lower probabilities of sustaining the muted pace of Arctic sea ice loss in the future, although the impact of this is subtle and not consistent for every model.

On average, the sea ice area in ensemble members which simulate pauses in sea ice loss for the period 2005-2024 is 0.5 million km^2 larger in 2025 than in ensemble members from the same models and scenarios in which there is no pause (Fig. 2c). This source of predictability decays within a decade, and after that the September sea ice area in ensemble members with and without pauses are indistinguishable from each other.

It is important to highlight that to produce these estimates, we have limited the model selection to only those models with at least five members which feature sea ice pauses in 2004-2025, because to compute these probabilities in a meaningful way requires that the remaining ensemble size is large enough. This may however, bias the results towards models with more ensemble members, which are more likely to include more members with slowdowns due to better sampling, and towards models which simulate slowdowns more frequently. The multi-model average of the probability of a sea ice loss pause in this smaller subset of members is 28%, which is higher than the 20% estimated from all models. If the observed slowdown is an inherently infrequent and rare event, then this approach would overestimate the probability of it continuing, and underestimate how anomalously high the Arctic sea ice cover is relative to the forced trend. However, of the models which can reproduce the observed trends, over two-thirds of the available models are included in this estimate. Our results are broadly consistent with the findings of Swart et al. (2015), which showed that multi-decadal pauses longer than 20-years were possible in the late 21st century under a medium emissions scenario.

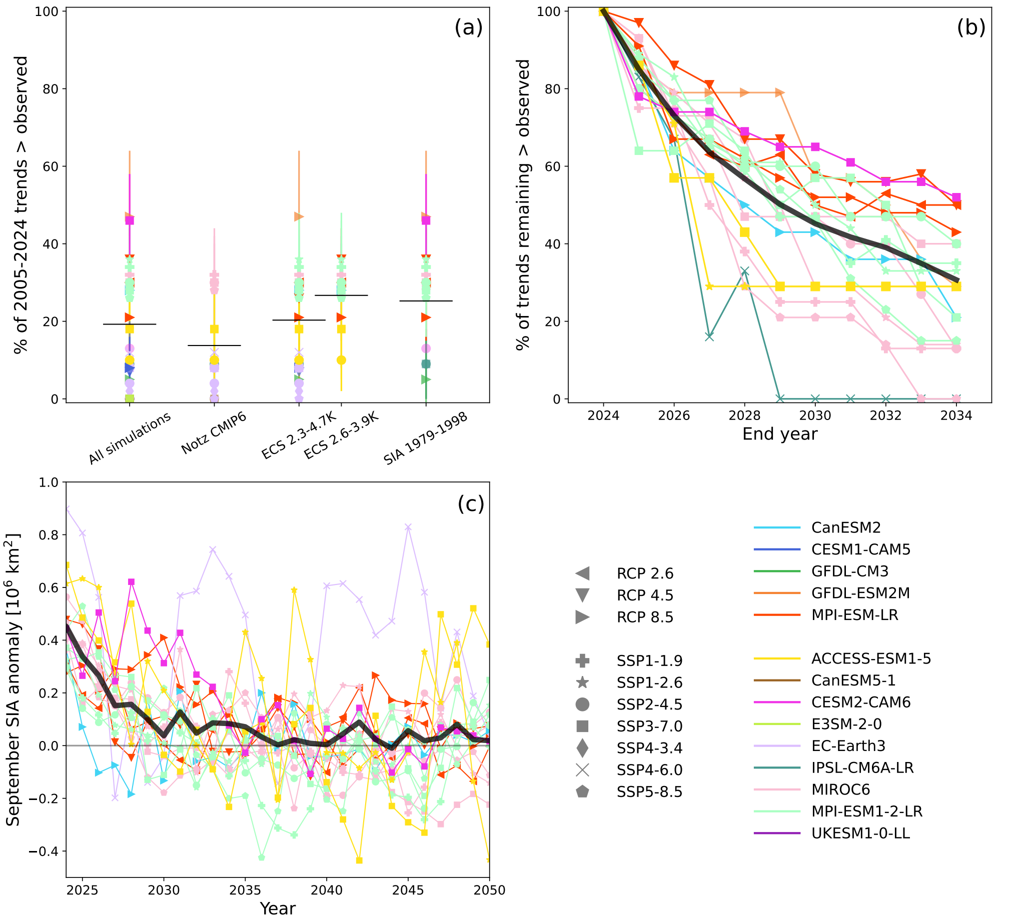

Figure 2. (a) The percentage of ensemble members [%] for each ensemble that have 2005-2024 September sea ice area loss trends less than the observed value. The uncertainty estimate is calculated by monte carlo simulation with replacement. All simulations are shown on the left, with different selection criteria (that outlined in Notz and SIMIP Community (2020), the 5-95% and 66% range of ECS (Sherwood et al., 2020), and the climatological sea ice area applied on the right. (b) The conditional probability across each ensemble for the trends starting in 2005 to continue to be above -0.29 10^6 km^2/decade for a given end year. (c) The ensemble-mean difference in September sea ice area [10^6 km^2] between ensemble members with and without ice loss pauses over 2005-2024 for the period 2025-2050. For panels (b) and (c) only models and scenarios with at least five members with 2005-2024 trends above observed were included, with the black line shows the weighted average according to Equation 1. In all panels, each colour represents a model and each symbol represents a different forcing scenario.

Taken together, the wealth of available CMIP5 and CMIP6 simulations suggest it is possible, perhaps even likely, that the present slowdown in sea ice decline may continue for a further 5-10 years. If that were the case it may then imply the occurrence of an early ice-free Arctic is less likely than raw model output would suggest (Jahn et al., 2016; Arthun et al., 2020; Wang et al., 2021; England & Polvani, 2023; Jahn et al., 2024).

3.4 Climate models suggest an important role for climate variability

Whether the present slowdown persists in the future or not, one final question remains to be answered: is the recent pause a response to anthropogenic forcings alone, or is there an important role for internal climate variability? When attempting to isolate the forced component of any observed trend from internal variability, it is important to keep in mind that - assuming the model simulations faithfully capture a plausible reality - the observations are expected to have the same broad features as individual ensemble members, i.e. that they are a combination of a forced trend plus one particular realization of internal variability (although one doesn't expect the observations to precisely match any one member). Given the well-established importance of internal climate variability in Arctic sea ice trends (Kay et al., 2011; Swart et al., 2015; England et al., 2019; Dörr et al., 2023), we next assess whether a change in the forced response could also be substantially contributing to the observed slowdown in ice loss.

First, we show the forced September sea ice loss for the period 2005-2024 as estimated by the linear trend of the ensemble mean for each model and scenario (Fig. 3, horizontal axis). We find there are only two model/scenario combinations (GFDL-ESM2M RCP8.5 and CESM2 SSP3-7.0) for which the forced trend is estimated to entirely explain observed trends in ice loss (shown in Fig. 3, as grey vertical lines) with minimal role for internal variability. Over 85% of the models we analyse here have a larger forced sea ice loss for this period than observed (as they lie to the left of the observed trends), implying that internal variability has acted to reduce the pace of ice loss.

Second, we ask: is there evidence that the forced response itself is slowing down relative to the previous two decades? On the vertical axis of Figure 3, therefore, we plot the ratio of the 2005-2024 forced trend to that of the preceding twenty years, 1986-2005, for each model and scenario combination: a ratio of 1.0 indicates no change in the pace of ice loss, > 1 indicates an acceleration and < 1 indicates a deceleration. Again we find that only GFDL-ESM2M RCP8.5 and CESM2 SSP3-7.0 suggest that the reduction in the forced trends accounts entirely for the observed slowdown. While the results from all the other models agree that this observed pause is not entirely a forced response, the remaining models are relatively evenly split (Fig. 3): roughly half the models suggest that the forced sea ice loss trend has modestly decelerated over the past two decades relative to the prior two decades, and roughly half suggest it has modestly accelerated (this is especially clear if we disregard the models which are unable to capture the observed recent trends).

In summary then: while the modelling evidence is uncertain as to whether anthropogenic forcings - even in part - for the recent slowdown in Arctic sea ice loss, it is very likely that internal climate variability is contributing to the slowdown in an important way.

4 Conclusion and Discussion

It is perhaps surprising that while global temperatures have risen rapidly, reaching record levels in the last few years, Arctic sea ice cover has shown no statistically significant decline over the past two decades. Nonetheless, analyzing two observational datasets and thousands of simulations from the CMIP5 and CMIP6 archives, we have established the following facts, which address the four questions raised in the introduction:

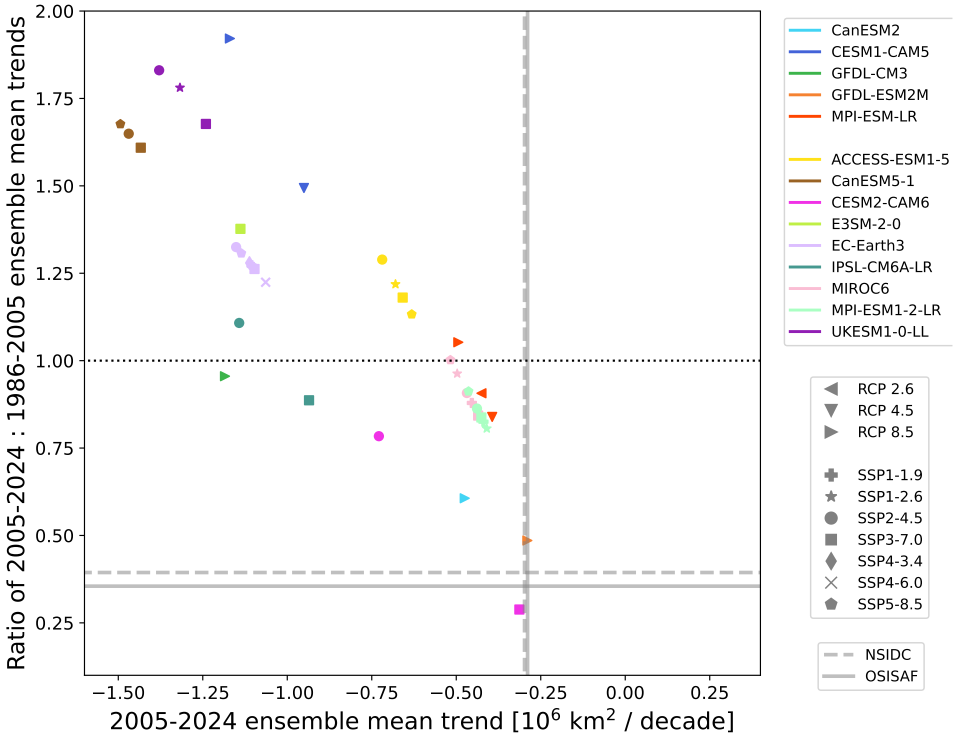

Figure 3. The ensemble mean trend in September sea ice area for the period 2005-2024 for each model and scenario (horizontal axis) versus the ratio of ensemble mean trends in September sea ice area for the periods 2005-2024 : 1986-2005 (vertical axis) with the black dotted line indicating a ratio of 1.0. Observational estimates of the 2005-2024 trend and the ratio of 2005-2024 : 1986-2005 trends are shown as grey lines (dashed line for NSIDC, solid line for OSISAF). Note that this does not imply that the observed trends are estimates of the forced response in the real climate system.

1. The pervasive slowdown of Arctic sea ice loss is robust across the choice of definitions, observational dataset, and season.
2. This observed pause in ice loss is simulated relatively frequently (with a 20% chance) in climate models, and is thus to be expected even under high emission scenarios.
3. If model simulations are accurate, the recent pause may plausibly continue for an additional five to ten years
4. Nearly all models analysed suggest an important role for internal climate variability in slowing the anthropogenically-forced sea ice loss.

We now return to the question of the contribution of human influence versus internal climate variability. If the slowdown is in fact a predominantly anthropogenically forced episode, our results suggest that there must be either some shared missing forcing or common model deficiency in response to the standard forcing among the majority of the models. While the latter part is difficult to assess, one culprit for a missing forcing could be the increase in boreal forest fires, not incorporated in standard scenarios. The recent study of Blanchard-Wrigglesworth et al. (2025) shows that incorporating recent biomass burning emissions into the CESM2 model leads to a rapid recovery of September sea ice cover during the period of interest due to increased reflection in the Northern Hemisphere of incoming shortwave radiation arising from the cloud response and aerosol cloud interactions. However, due to specifics of the simulation of polar clouds in CESM2 (DeRepentigny et al., 2022; Zhu et al., 2022; Davis & Medeiros, 2024; England & Feldl, 2024), and a seemingly opposite result from similar experiments with a different climate model (Zhong et al., 2024), further experiments with a wider range of models are needed to understand the role changes in biomass burning have had on observed Arctic sea ice trends.

Going forward, how can we use what we have learned about the recent pause in Arctic sea ice loss? Firstly, if internal variability has played an important role then this could provide a source of future predictability of Arctic climate change in the same manner as Yeager et al. (2015). And second, this period could be used as an out of sample test in future climate model evaluation – similar to the early and middle periods of the 20th century (Flynn et al., 2023; Bianco et al., 2024; Chen & Dai, 2024). However, overall this study is a reminder that we should be humble about multi-decadal predictions of the climate system, especially in highly variable regions such as the Arctic. Standing in 2007 or 2012 after having experienced another year of record loss and listening to assessments that climate models are flawed in their ability to reproduce the rapid loss of Arctic sea ice (Stroeve et al., 2007), it would take a rather brave person to have predicted that a sustained slowdown in ice loss was around the corner, although, as we have shown, and many have found before (Kay et al., 2011; Swart et al., 2015; R. Zhang, 2015), this is entirely consistent with what climate models simulate.

Open Research Section

All CMIP5 and CMIP6 data analysed in this study is publicly available to download from the Earth System Federation Grid at https://aims2.llnl.gov/search.

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References

Arthun, M., Onarheim, I., Dörr, J., & Eldevik, T. (2020). The seasonal and regional transition to an ice-free Arctic. *Geophysical Research Letters*, *48*(e2020GL090825). doi: 10.1029/2020GL0909825

Baxter, I., Ding, Q., Schweiger, A., L'Heureux, M., Baxter, S., Wang, T., ... Lu, J. (2019). How tropical Pacific surface cooling contributed to accelerated sea ice melt from 2007 to 2012 as ice is thinned by anthropogenic forcing. *Journal of Climate*, *32*, 8583-8602. doi: 10.1175/JCLI-D-18-0783.1

Bianco, E., Blanchard-Wrigglesworth, E., Materia, S., Ruggieri, P., Iovino, D., & Masina, S. (2024). CMIP6 models underestimate Arctic sea ice loss during the early twentieth-century warming, despite simulating large low-frequency sea ice variability. *Journal of Climate*, *37*, 6305-6321. doi: 10.1175/JCLI-D-23-0647.1

Blanchard-Wrigglesworth, E., DeRepentigny, P., & Frierson, D. (2025). Increasing boreal fires reduce future global warming and sea ice loss. *Preprint*. doi: 10.21203/rs.3.rs-5486231/v2

Chen, X., & Dai, A. (2024). Quantifying contributions of external forcing and internal variability to Arctic warming during 1900-2021. *Earth's Future*, *12*(e2023EF003734). doi: 10.1029/2023EF003734

Copernicus, E. (2024, April). *Climate indicators.* Retrieved 16/02/2025, from https://climate.copernicus.eu/climate-indicators

Davis, I., & Medeiros, B. (2024). Assessing CESM2 clouds and their response to climate change using cloud regimes. *Journal of Climate*, *37*, 2965-2985. doi: 10.1175/JCLI-D-23-0337.1

DeRepentigny, P., Jahn, A., Holland, M., Kay, J., Fasullo, J., Lamarque, J., ... Barrett, A. (2022). Enhanced simulated early 21st century Arctic sea ice loss due to CMIP6 biomass burning emissions. *Science Advances*, *8*(30). doi: 10.1126/sciadv.abo2405

Deser, C., & Phillips, A. (2021). Defining the internal component of Atlantic Multidecadal Variability in a changing climate. *Geophysical Research Letters*, *48*(e2021GL095023). doi: 10.1029/2021GL095023

Ding, Q., Schweiger, A., L'Heureux, M., Steig, E., Battisti, D., Johnson, N., ... Baxter, I. (2018). Fingerprints of internal drivers of Arctic sea ice loss in observations and model simulations. *Nature Geoscience*, *12*, 28-33. doi: 10.1038/s41561-018-0256-8

Dörr, J., Bonan, D., Arthun, M., Svendsen, L., & Wills, R. (2023). Forced and internal components of observed Arctic sea-ice changes. *The Cryosphere*, *17*, 4133-4153. doi: 10.5194/tc-17-4133-2023

England, M. (2021). Are multi-decadal fluctuations in arctic and antarctic surface temperatures a forced response to anthropogenic emissions or part of internal climate variability? *Geophysical Research Letters*, *48*(e2020GL090631). doi: 10.1029/2020GL090631

England, M., Eisenman, I., Lutsko, N., & Wagner, T. (2021). The recent emergence of Arctic Amplification. *Geophysical Research Letters*, *48*(e2021GL094086). doi: 10.1029/2021GL094086

England, M., & Feldl, N. (2024). Robust polar amplification in ice-free climates relies on ocean heat transport and cloud radiative effects. *Journal of Climate*, *37*, 2179-2197. doi: 10.1175/JCLI-D-23-0151.1

England, M., Jahn, A., & Polvani, L. (2019). Nonuniform contribution of internal variability to recent Arctic sea ice loss. *Journal of Climate*, *32*, 4039-4053. doi: 10.1175/JCLI-D-18-0864.1

England, M., & Polvani, L. (2023). The Montreal Protocol is delaying the occurrence of the first ice-free Arctic summer. *PNAS*, *120*(e2211432120). doi: 10.1073/pnas.2211432120

Fetterer, F., Knowles, K., Meier, W., Savoie, M., & Windnagel, A. (2017). *Sea ice index. (g02135, version 3).* [dataset]. National Snow and Ice Data Center. doi: 10.7265/N5K072F8

Flynn, C., Huusko, L., Modak, A., & Mauritsen, T. (2023). Strong aerosol cooling alone does not explain cold-biased mid-century temperatures in CMIP6 models. *Atmospheric Chemistry and Physics*, *23*, 15,121-15,133. doi: 10.5194/acp-23-15121-2023

Francis, J., & Wu, B. (2020). Why has no new record-minimum Arctic sea-ice extent occurred since september 2012? *Environmental Research Letters*, *15*(114034). doi: 10.1088/1748-9326/abc047

Fyfe, J., von Salzen, K., Gillett, N., Arora, V., Flato, G., & McConnell, J. (2013). One hundred years of Arctic surface temperature variation due to anthropogenic influence. *Scientific Reports*, *3*(2645). doi: 10.1038/srep02645

Gagne, M., Fyfe, J., Gillett, N., Polyakov, I., & Flato, G. (2017). Aerosol-driven increase in Arctic sea ice over the middle of the twentieth century. *Geophysical Research Letters*, *44*, 7338-7346. doi: 10.1002/2016GL071941

Hansen, J., Kharecha, P., Sato, M., Tselioudis, G., Kelly, J., Bauer, S., ... Pokela, A. (2025). Global warming has accelerated: Are the United Nations and the public well-informed? *Environment: Science and Policy for Sustainable Development*, *67*, 6-44. doi: 10.1080/00139157.2025.2434494

IPCC. (2021). Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the Intergovernmental Panel on Climate Change. In V. Masson-Delmotte et al. (Eds.), (p. 3-32). Cambridge University Press.

Jahn, A., Holland, M., & Kay, J. (2024). Projections of an ice-free Arctic Ocean. *Nature Reviews Earth and Environment*, *5*, 167-176. doi: 10.1038/s43017-023-00515-9

Jahn, A., Kay, J., Holland, M., & Hall, D. (2016). How predictable is the timing of a summer ice-free Arctic? *Geophysical Research Letters*, *43*, 9113-9120. doi: 10.1002/2016GL070067

Kay, J., Holland, M., & Jahn, A. (2011). Inter-annual to multi-decadal Arctic sea ice extent trends in a warming world. *Geophysical Research Letters*, *38*(L15708). doi: 10.1029/2011GL048008

Kerr, R. (2000). A North Atlantic climate pacemaker for the centuries. *Science*, *288*, 1984-1985. doi: 10.1126/science.288.5473.1984

Kwok, R. (2018). Arctic sea ice thickness, volume, and multiyear ice coverage: losses and coupled variability (1958–2018). *Environmental Research Letters*, *13*, 105005. doi: 10.1088/1748-9326/aae3ec

Lee, Y., & Liu, W. (2023). The weakened Atlantic Meridional Overturning Circulation diminishes recent Arctic sea ice loss. *Geophysical Research Letters*, *50*(e2023GL105929). doi: 10.1029/2023GL105929

Lund, M., Myhre, G., & Samset, B. (2019). Anthropogenic aerosol forcing under the Shared Socioeconomic Pathways. *Atmospheric Chemistry and Physics*, *19*, 13827-13839. doi: 10.5194/acp-19-13827-2019

Manshausen, P., Watson-Parris, D., Christensen, M., Jalkanen, J., & Stier, P. (2022). Invisible ship tracks show large cloud sensitivity to aerosol. *Nature*, *610*, 101–106. doi: 10.1038/s41586-022-05122-0

Mantua, N., & Hare, S. (2002). The Pacific Decadal Oscillation. *Journal of Oceanography*, *58*, 35-44. doi: 10.1023/A:1015820616384

Maslowski, W., Kinney, J., Higgins, M., & Roberts, A. (2012). The future of Arctic sea ice. *Annual Review of Earth and Planetary Sciences*, *40*, 625-654. doi: 10.1146/annurev-earth-042711-105345

Meehl, G., Chung, C., Arblaster, J., Holland, M., & Bitz, C. (2018). Tropical decadal variability and the rate of Arctic sea ice decrease. *Geophysical Research Letters*, *45*, 11,326-11,333. doi: 10.1029/2018GL079989

Meehl, G., Senior, C., Eyring, V., Lamarque, J., Stouffer, R., Taylor, K., & Schlund, M. (2020). Context for interpreting equilibrium climate sensitivity and transient climate response from the CMIP6 Earth system models. *Science Advances*, *6*(eaba1981). doi: 10.1126/sciadv.aba1981

Meier, W., & Stewart, J. (2019). Assessing uncertainties in sea ice extent climate indicators. *Environmental Research Letters*, *14*(035005). doi: 10.1088/1748-9326/aaf52c

Merchant, C., Allan, R., & Embury, O. (2025). Quantifying the acceleration of multidecadal global sea surface warming driven by Earth's energy imbalance. *Environmental Research Letters*, *20*(024037). doi: 10.1088/1748-9326/adaa8a

Nafaji, M., Zwiers, F., & Gillett, N. (2015). Attribution of Arctic temperature change to greenhouse-gas and aerosol influences. *Nature Climate Change*, *5*, 246-249. doi: 10.1038/nclimate2524

Notz, D., & SIMIP Community. (2020). Arctic sea ice in CMIP6. *Geophysical Research Letters*, *47*(e2019GL086749). doi: 10.1029/2019GL086749

Notz, D., & Stroeve, J. (2016). Observed Arctic sea-ice loss directly follows anthropogenic CO2 emission. *Science*, *354*, 747-750. doi: 10.1126/science.aag2345

Onarheim, I., Arthun, M., Teigen, S., Eik, K., & Steele, M. (2024). Recent thickening of the Barents Sea ice cover. *Geophysical Research Letters*, *51*(e2024GL108225). doi: 10.1029/2024GL108225

OSI-420. (2023). *Osi saf sea ice index 1978-onwards, version 2.2.* [dataset]. EUMETSAT Ocean and Sea Ice Satellite Application Facility. doi: 10.15770/EUM_SAF_OSI_0022

Parkinson, C., & Comiso, J. (2013). On the 2012 record low Arctic sea ice cover: Combined impact of preconditioning and an August storm. *Geophysical Research Letters*, *40*, 1356-1361. doi: 10.1002/grl.50349

Rantanen, M., Karpechko, A., Lipponen, A., Hyvarinen, O., Ruosteenoja, K., Vihma, T., & Laaksonen, A. (2022). The Arctic has warmed nearly four times faster than the globe since 1979. *Communications Earth and Environment*, *3*(168). doi: 10.1038/s43247-022-00498-3

Samset, B., Zhou, C., Fuglestvedt, J., Lund, M., Marotzke, J., & Zelinka, M. (2023). Steady global surface warming from 1973 to 2022 but increased warming rate after 1990. *Communications Earth and Environment*, *4*(400). doi: 10.1038/s43247-023-01061-4

Schweiger, A., Lindsay, R., Zhang, J., Steele, M., Stern, H., & Kwok, R. (2011). Uncertainty in modeled Arctic sea ice volume. *Journal of Geophysical Research*, *116*(C00D06). doi: 10.1029/2011JC007084

Shen, Z., Duan, A., Zhou, W., Peng, Y., & Li, J. (2024). Reconciling roles of external forcing and internal variability in Arctic sea ice change on different time scales. *Journal of Climate*, *37*, 3577-3591. doi: 10.1175/JCLI-D-23-0280.1

Sherwood, S., Webb, M., Annan, J., Armour, K., Forster, P., Hargreaves, J., … Zelinka, M. (2020). An assessment of Earth's climate sensitivity using multiple lines of evidence. *Review of Geophysics*, *58*(e2019RG000678). doi: 10.1029/2019RG000678

Siew, P., Wu, Y., Ting, M., Zheng, C., Ding, Q., & Seager, R. (2024). Significant contribution of internal variability to recent Barents–Kara sea ice loss in winter. *Communications Earth and Environment*, *5*(411). doi: 10.1038/s43247-024-01582-6

Stroeve, J., Holland, M., Meier, W., Scambos, T., & Serreze, M. (2007). Arctic sea ice decline: faster than forecast. *Geophysical Research Letters*, *34*(L09501). doi: 10.1029/2007GL029703

Stroeve, J., & Notz, D. (2018). Changing state of Arctic sea ice across all seasons. *Environmental Research Letters*, *13*(103001). doi: 10.1088/1748-9326/aade56

Stroeve, J., Serreze, M., Drobot, S., Gearhead, S., Holland, M., Maslanika, J., … Scambos, T. (2011). Arctic sea ice extent plummets in 2007. *Eos*, *89*, 13-14.

doi: 10.1029/2008EO020001

Swart, N., Fyfe, J., Hawkins, E., Kay, J., & Jahn, A. (2015). Influence of internal variability on arctic sea-ice trends. *Nature Climate Change*, *5*, 86-89. doi: 10.1038/nclimate2483

Szopa, S., Balkanski, Y., Schulz, M., Bekki, S., Cugnet, D., Fortems-Cheiney, A., ... Dufresne, J. (2013). Aerosol and ozone changes as forcing for climate evolution between 1850 and 2100. *Climate Dynamics*, *40*, 2223-2250. doi: 10.1007/s00382-012-1408-y

Wadhams, P. (2016). *A farewell to ice*. Penguin Publishing.

Walsh, J., Fetterer, F., Scott, J., & Chapman, W. (2017). A database for depicting Arctic sea ice variations back to 1850. *Geographical Review*, *107*, 89-107. doi: 10.1111/j.1931-0846.2016.12195.x

Wang, B., Zhou, X., Ding, Q., & Liu, J. (2021). Increasing confidence in projecting the Arctic ice-free year with emergent constraints. *Environmental Research Letters*, *16*(094016). doi: 10.1088/1748-9326/ac0b17

Yeager, S., Karspeck, A., & Danabasoglu, G. (2015). Predicted slowdown in the rate of Atlantic sea ice loss. *Geophysical Research Letters*, *42*, 10,704-10,713. doi: 10.1002/2015GL065364

Yoshioka, M., Grosvenor, D., Booth, B., Morice, C., & Carslaw, K. (2024). Warming effects of reduced sulfur emissions from shipping. *Atmospheric Chemistry and Physics*, *24*, 13681–13692. doi: 10.5194/acp-24-13681-2024

Zhang, J. (2021). Recent slowdown in the decline of Arctic sea ice volume under increasingly warm atmospheric and oceanic conditions. *Geophysical Research Letters*, *48*(e2021GL094780). doi: 10.1029/2021GL094780

Zhang, J., Lindsay, R., Schweiger, A., & Steele, M. (2013). The impact of an intense summer cyclone on 2012 Arctic sea ice retreat. *Geophysical Research Letters*, *40*, 720-726. doi: 10.1002/grl.50190

Zhang, R. (2015). Mechanisms for low-frequency variability of summer Arctic sea ice extent. *PNAS*, *112*, 4570-4575. doi: 10.1073/pnas.1422296112

Zhong, Q., Shutgens, N., Veraverbeke, S., & van der Werf, G. (2024). Increasing aerosol emissions from boreal biomass burning exacerbate Arctic warming. *Nature Climate Change*, *14*, 1275-1281. doi: 10.1038/s41558-024-02176-y

Zhu, J., Otto-Bliesner, B., Brady, E., Gettelman, A., Bacmeister, J., Neale, R., ... Kay, J. (2022). LGM paleoclimate constraints inform cloud parameterizations and equilibrium climate sensitivity in CESM2. *Journal of Advances in Modeling Earth Systems*, *14*(e2021MS002776). doi: 10.1029/2021MS002776

Surprising, but not unexpected, multi-decadal pause in Arctic sea ice loss

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Key Points:

- The loss of Arctic sea ice cover has undergone a pronounced slowdown over the past two decades, across all months of the year.
- Rather than being an unexpected rare event, comprehensive climate models from CMIP5 and CMIP6 simulate such pauses relatively frequently.
- According to these climate model simulations, this pause in the loss of Arctic sea ice could plausibly continue for the next 5-10 years.

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Abstract

Over the past two decades, Arctic sea ice loss has slowed considerably, with no statistically significant decline in September sea ice area since 2005. This pause is robust across observational datasets, metrics, and seasons. Large-ensemble CMIP5 and CMIP6 simulations reveal that such periods with no sea ice decline under increasing greenhouse gas emissions are not unusual. Analysis of ensemble members that simulate analogues of the observed pause indicates that the current slowdown could plausibly persist another five to ten years. The modelling evidence suggests that internal variability has substantially offset anthropogenically forced sea ice loss in recent decades, although possible contributions from changes in the forced response remain uncertain. Overall, this observed pause in Arctic sea ice decline is consistent with simulated internal variability superimposed on the long term trend according to the bulk of the climate modelling evidence.

Plain Language Summary

Over the last 20 years, the decline of Arctic sea ice has slowed down substantially. Climate models (from CMIP5 and CMIP6) show that pauses in sea ice loss across multiple decades can happen, even as greenhouse gas emissions continue to rise. When we compare the current slowdown to similar pauses in model simulations, we see that this "hiatus" could plausibly continue for another five to ten years. Most of the evidence from these climate models suggests that natural climate variations have played a large part in slowing the human-driven loss of sea ice. However, it is not entirely certain whether changes in the human influence on climate (the "forced response") have also contributed. Overall, while it may sound surprising that Arctic sea ice loss has slowed down even as global temperatures hit record highs, the climate modelling evidence suggests we should expect periods like this to occur somewhat frequently.

1 Introduction

The loss of Arctic sea ice over the past half century is one of the most clear and well-known indicators of human-induced climate change (IPCC, 2021; Copernicus, 2024). September sea ice area has nearly halved since the beginning of the satellite era in 1979 (Fetterer et al., 2017; Stroeve & Notz, 2018), and during the same period, estimated Arctic sea ice volume has decreased by over 10,000 km^3 (Kwok, 2018). Record-breaking summer sea ice minimums in 2007 (Stroeve et al., 2011) and 2012 (Parkinson & Comiso, 2013; J. Zhang et al., 2013) fuelled predictions, which with hindsight look overly alarmist, that the Arctic would experience its first ice-free summer before 2020 (Maslowski et al., 2012; Wadhams, 2016). Adding to this, the Arctic has been warming up to four times faster than the global average (Rantanen et al., 2022). It has been further proposed that global warming might be accelerating, culminating in record breaking warmth in recent years (Samset et al., 2023; Hansen et al., 2025; Merchant et al., 2025). As Arctic sea ice cover is strongly tied to global temperatures (Notz & Stroeve, 2016), there would be little expectation of a multi-decadal *slowdown* in Arctic sea ice loss. And yet, as we will show, such a slowdown has been occurring in the last two decades.

Recall that, over the past century, periods of increasing anthropogenic greenhouse emissions without sustained sea ice loss - the mid-20th century (Walsh et al., 2017) - have already occurred. From the 1940s to the 1970s Arctic sea ice cover *expanded* (Gagne et al., 2017), with the largest increases in the Chukchi, East Siberian, Laptev, Kara and Barents Seas. However, anthropogenic forcing in the mid-20th century was very different compared to the one of the past two decades. Industrial aerosol emissions from Europe and North America contributed substantially to the positive multi-decadal trend in Arctic sea ice area and associated Arctic cooling in the mid-20th century (Fyfe et al., 2013; Nafaji et al., 2015; Gagne et al., 2017; England et al., 2021); but these aerosol sources are far smaller today (Szopa et al., 2013; Lund et al., 2019). However, when anthropogenic aerosols are being discussed in the context of the recent past, it is with regards to the phase out of aerosol emissions from ship tracks which have potentially contributed to enhanced global warming since 2020 (Manshausen et al., 2022; Yoshioka et al., 2024). In fact, Yoshioka et al. (2024) find that the simulated warming response to these reduced sulphur emissions is largest in the Arctic. So, the lessons of the past may not be a reliable guide for understanding current trends.

It is important to appreciate that the observed trend in Arctic sea ice cover over a given period is composed of a contribution caused by anthropogenic emissions, denoted the forced response, and a contribution from unforced fluctuations associated with internal climate variability (England et al., 2019; England, 2021; Dörr et al., 2023; Shen et al., 2024). Anthropogenically-forced changes which may contribute to a reduction in Arctic sea ice loss over the past two decades include a forced slowdown in the Atlantic Meridional Overturning Circulation (Lee & Liu, 2023), and changes in the emissions from biomass burning, both in the magnitude (Blanchard-Wrigglesworth et al., 2025), and the variability (DeRepentigny et al., 2022). One would imagine, however, that the aforementioned reduction of sulphur emission from shiptracks (Yoshioka et al., 2024) would lead to an acceleration rather than a deceleration of sea ice loss since 2020. Alternatively modes of climate variability which act on multi-decadal timescales, such as the Atlantic Multidecadal Oscillation (Kerr, 2000; Deser & Phillips, 2021) and the Pacific Decadal Oscillation (Mantua & Hare, 2002), have an important imprint on Arctic sea ice. For example, variability emanating from the Pacific sector (Ding et al., 2018; Baxter et al., 2019) or Atlantic sector (Meehl et al., 2018) has been suggested to have substantially contributed to the rapid loss of Arctic sea ice during the 2000s (England et al., 2019). A number of recent studies, using different methods including standard optimal detection method (Shen et al., 2024), machine learning (Siew et al., 2024) and low-frequency component analysis (Dörr et al., 2023), conclude that internal variability is at least as important as anthropogenic forcing, perhaps more, for explaining the steep decline in that period. Needless to say, internal variability can damp sea ice loss trends as well as strengthen them. For instance, Yeager et al. (2015) correctly predicted a slowdown of winter Atlantic sector sea ice loss for the past decade based on predictability from oceanic conditions linked to the North Atlantic Oscillation.

In fact, it has been found in climate model simulations that internal climate variability can totally counteract the forced loss of Arctic sea ice, resulting in periods of simulated sea ice growth under increasing anthropogenic emissions. Kay et al. (2011) were among the first to demonstrate, in a single climate model, that positive trends in Arctic sea ice extent on multi-decadal timescales were possible until the middle of this century. They found, using a limited ensemble size of six members, that two members exhibited statistically insignificant trends in September for the period 1979-2005 due to a cancellation between the forced response and internal climate variability. Motivated by the as-of-then brief pause in September Arctic sea ice loss for the period 2007-2013, Swart et al. (2015) analyzed the CMIP5 archive and showed that seven-year pauses occurred frequently in model simulations, and concluded that such episodes are an expected feature of Arctic sea ice trajectory, even in a high emissions scenario. This study also demonstrated that pauses in sea ice loss on multi-decadal timescales remain plausible, and relatively frequent, over the coming century under a medium- or low-emissions scenario. Looking back from the vantage point of 2025, the model-based studies of Kay et al. (2011) and Swart et al. (2015) now appear remarkably prescient with regards to the plausibility of a sustained slowdown in Arctic sea ice loss.

In this paper we document the recent observed multi-decadal pause in Arctic sea ice loss and address the following questions:

1. How extensive and robust is this pause in Arctic sea ice loss?

2. Are comprehensive climate models able to capture this observed phenomenon, and if so how likely is it suggested to be?
3. How long could this observed pause plausibly persist for?
4. What is the role of anthropogenic forcing versus internal climate variability in contributing to the slow rate of sea ice loss?

2 Data and Methods

To investigate the evolution in Arctic sea ice cover, we utilise both the NSIDC (Fetterer et al., 2017) and the OSISAF (OSI-420, 2023) sea ice indices. Both of these are continually updated data records of the Arctic sea area and extent, for the period 1979 - present, derived from satellite measurements. We note that there are known systematic differences in the mean state between the two products (Meier & Stewart, 2019) but their interannual variations and multi-decadal trends have strong similarities (Figures 1a,b and S1). For understanding changes in the simulated Arctic sea ice volume we utilise the Pan-Arctic Ice Ocean Modeling and Assimilation System (PIOMAS) product (Schweiger et al., 2011).

To investigate the frequency and length of pauses in Arctic sea ice loss in comprehensive climate model simulations, we here analyze all available large ensemble simulations from the CMIP5 and CMIP6 archive. Any model with at least ten members is used, as summarised in Table S1. For the CMIP5 models, we use historical simulations which terminate at the year 2005, followed by the ScenarioMIP simulations with a range of Representative Concentration Pathways (RCPs). For the CMIP6 models, we use historical simulations up to the year 2014, followed by ScenarioMIP simulations with a range of Shared Socioeconomic Pathways (SSPs).

The main approach for analysing simulated changes in Arctic sea ice cover is to compute the linear trend for the twenty-year period 2005-2024 for each individual member available for each model, as motivated by the observed changes (Section 3.1). This gives a range between 10 and 100 members to examine the spread of simulated trends for each model and scenario. To check for robustness by looking over a large sample size, we also expand the overall time period by ten years each side (1995-2034), or shorter if the ensemble mean has transitioned to ice-free conditions before 2035, and then calculate all of the possible 20-year trends during this period; this, however, does not substantially alter the results. The main definition of slowdown used in this study is motivated by the observed 2005-2024 September sea ice area trends (> -0.29 million km^2/dec). We also use an alternative definition – trends which are not statistically significant at the 95% confidence level – to ensure that this specific observed threshold does not overly influence the results. This secondary definition contains information about the signal to noise ratio, and so is complementary to the trend threshold definition. However, we find that both definitions produce consistent results.

When we report multi-model averages, we do so by using a square-root weighting scheme to take account of the number of members in each ensemble (models with more members are weighted higher because the larger sample size will provide a more robust estimate of the probability of a slowdown occurring) and the number of scenarios (models with more scenarios are down-weighted because they are not independent of each other). Doing this ensures that models with multiple scenarios are treated as if they have more members of the same model scenario. The weighting for each model i and scenario j of a given selection, where the number of members for each model for a given scenario is n_{ij} and the number of scenarios for each model is given by s_i is calculated as:

$$w_{ij} = \frac{\sqrt{a_{ij}}/\sqrt{s_i}}{\sum_{i,j}[\sqrt{a_{ij}}/\sqrt{s_i}]} \tag{1}$$

However, we emphasize that this weighting scheme does not substantially alter the conclusions compared to if all members were weighted equally (not shown).

3 Results

3.1 A robust and sustained pause in Arctic sea ice loss

We first investigate the recent observed trends in Arctic sea ice cover, focusing on the annual minimum, September. The trend of September Arctic sea ice area for the most recent two decades 2005-2024 is -0.30 and -0.29 million km^2 per decade according to the NSIDC and OSISAF sea ice indices respectively (Fig. 1a,b). The key point, we emphasize, is that these trends are not statistically significantly different from zero at a 95% confidence level. This is also seen in Figure 1c,d where 20-year trends are plotted versus the end year: note how trends ending in 2024 retreat inside the uncertainty envelope. According to the OSISAF record, the 2005-2024 trend is the slowest rate of sea ice area loss over any 20-year period since the start of the satellite record. For both datasets, this insignificant trend is approximately four-times smaller than the peak 20-year sea ice loss trend recorded (1993-2012). These results are robust to the choice of sea ice area or sea ice extent (Fig. S1). The slowdown in September sea ice loss mainly occurs in the Pacific and Eurasian sector, from the Beaufort Sea westward to the Barents Sea (not shown).

While sea ice loss in September is of particular interest because that month is the annual minimum, the current pause in Arctic sea ice loss is seen in every single month throughout the year, as shown in Figure 1e,f). This suggests that the underlying mechanism(s) must explain not just the summer trends (R. Zhang, 2015; Francis & Wu, 2020) or winter trends (Yeager et al., 2015), but sea ice trends throughout the entire year.

The same picture - indicating a severe slowdown in Arctic sea ice loss - also emerges when considering sea ice volume. The loss of Arctic sea ice volume has stalled for at least the past fifteen years (Fig. S2). For the period 2010-2024, the simulated annual mean Arctic sea ice volume has an approximately flat trend, decreasing by only 0.4 million km^3 per decade, a value that is 7-times smaller than the long-term simulated loss for the period 1979-2024 of 2.9 million km^3 per decade, and again is not statistically significant. This result, which is most evident in the Barents Sea (Onarheim et al., 2024), is consistent with a recent analysis suggesting a net build-up of sea ice volume since 2007 due to a decrease in ice export from the Arctic, in addition to the thinner ice cover exhibiting higher growth rates (J. Zhang, 2021).

Given the strong observational evidence for a sustained and pervasive pause in Arctic sea ice loss over the recent 15-20 years, highly robust to the choice of sea ice metric, observational product, and season, we are led to ask: is such a pause unexpected? To answer that question we turn to analyzing comprehensive climate model simulations. We seek to determine if they are able to capture pauses such as the observed one and, if so, to establish if such pauses are exceedingly rare or relatively frequent events.

3.2 Comprehensive climate models suggest 20-year pauses are not rare

To understand whether comprehensive climate models can simulate a multi-decadal pause of Arctic sea ice loss, we search through the CMIP5 and CMIP6 large ensemble archive to identify members which exhibit ice loss pauses. Consistent with previous studies (Kay et al., 2011; Swart et al., 2015; Lee & Liu, 2023), we find that nearly all models are able to simulate reductions in September Arctic sea ice area smaller than observed during the period 2005-2024. The two models which do not feature any such trends, UKESM1-0-LL and CanESM5-1, are both models with large climate sensitivities (Meehl et al., 2020), for which overly strong anthropogenically-forced sea ice loss does not allow for pauses such as the observed one.

Figure 2a shows the percentage of members with sea ice loss smaller than observed. The main result here is that the multi-model average suggests an approximately 20% chance of this pause in Arctic sea ice loss (Fig. 2a, column 1). However, we note a large spread

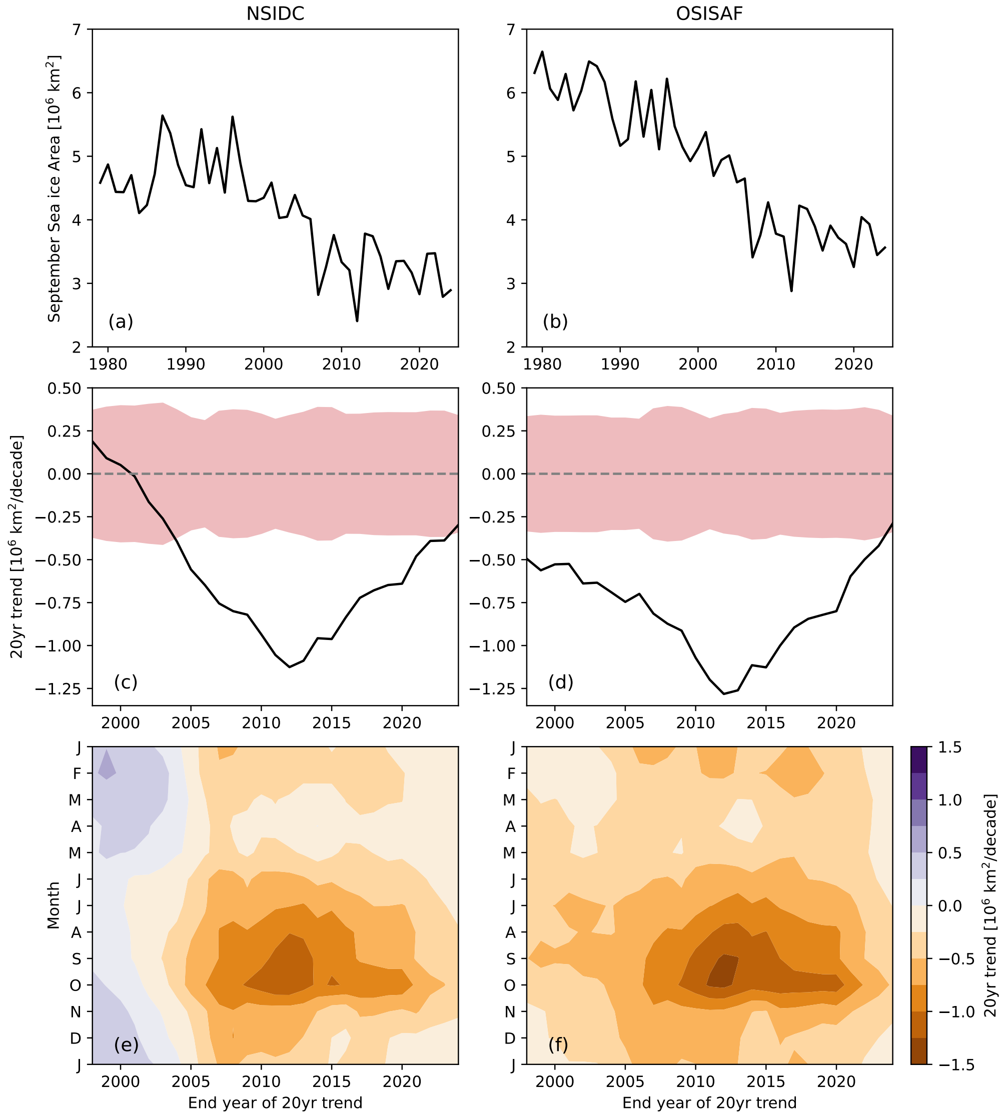

Figure 1. (a,b) Observed sea ice area [10^6 km^2] 1979-2024, (c,d) 20 year-trends of September sea ice area [10^6 km^2/decade] with varying end year from 1998 to 2024, in which the red shaded envelope shows the bounds inside which a linear trend is not statistically significant according to a t-test at 95% confidence and (e,f) the 20 year-trends of sea ice area with varying end years but for each month of the year. The left column (a,c,e) shows the NSIDC sea index (Fetterer et al., 2017) and the right column (b,d,f) shows the OSISAF sea ice index (OSI-420, 2023).

across the CMIP5 and CMIP6 models, with the probability of a smaller-than-observed 2005-2024 trend varying from 0% and approximately 50%. Interestingly, the spread across models for a given scenario is much larger than the spread across scenarios for a given model. This is perhaps unsurprising because the scenarios diverge from each other later than the 2020s (Notz & SIMIP Community, 2020), especially for the case of the CMIP6 forcing.

The central estimated value of approximately 20% doesn't change substantially if models are selected following the criteria from Notz and SIMIP Community (2020), or using models lying in the 66% range and 5-95% range estimates of the climate sensitivity (Sherwood et al., 2020), or using models according to their ability to simulate climatological sea ice conditions for the period 1979-1998 (Fig. 2a, column 2-4). Nor is the central estimate substantially impacted if we assess the probability of a non-statistically significant trend (Figure S3): this value is only slightly higher at approximately 25%. Therefore from the multi-model perspective, what we have observed in the Arctic over the past two decades is not a rare event, but rather one that should be expected to happen with reasonable frequency. This result is insensitive to how models are sub-selected, or to the metric of interest. This then raises the question of whether this pause in Arctic sea ice loss could continue and for how long.

3.3 The observed pause in sea ice loss could foreseeably continue for another decade

To investigate how much longer this current pause is likely to last into the future, we now examine those large ensemble members which do exhibit muted sea ice loss in the period from 2005-2024 (Fig. 2a), and quantify how long the simulated slowdowns persist in the future (Fig. 2b). In essence this produces the conditional probability estimate of the 20-year pause extending further for each model and scenario. The multi-model average suggests that pauses in September sea ice loss for the period 2005-2024 have a 1 in 2 chance of persisting for a further five years, and a 1 in 3 chance of persisting for a further ten years (note, however, the considerable intermodel spread of $\pm$ 25%). On average, higher emissions scenarios tend to show slightly lower probabilities of sustaining the muted pace of Arctic sea ice loss in the future, although the impact of this is subtle and not consistent for every model.

On average, the sea ice area in ensemble members which simulate pauses in sea ice loss for the period 2005-2024 is 0.5 million km^2 larger in 2025 than in ensemble members from the same models and scenarios in which there is no pause (Fig. 2c). This source of predictability decays within a decade, and after that the September sea ice area in ensemble members with and without pauses are indistinguishable from each other.

It is important to highlight that to produce these estimates, we have limited the model selection to only those models with at least five members which feature sea ice pauses in 2004-2025, because to compute these probabilities in a meaningful way requires that the remaining ensemble size is large enough. This may however, bias the results towards models with more ensemble members, which are more likely to include more members with slowdowns due to better sampling, and towards models which simulate slowdowns more frequently. The multi-model average of the probability of a sea ice loss pause in this smaller subset of members is 28%, which is higher than the 20% estimated from all models. If the observed slowdown is an inherently infrequent and rare event, then this approach would overestimate the probability of it continuing, and underestimate how anomalously high the Arctic sea ice cover is relative to the forced trend. However, of the models which can reproduce the observed trends, over two-thirds of the available models are included in this estimate. Our results are broadly consistent with the findings of Swart et al. (2015), which showed that multi-decadal pauses longer than 20-years were possible in the late 21st century under a medium emissions scenario.

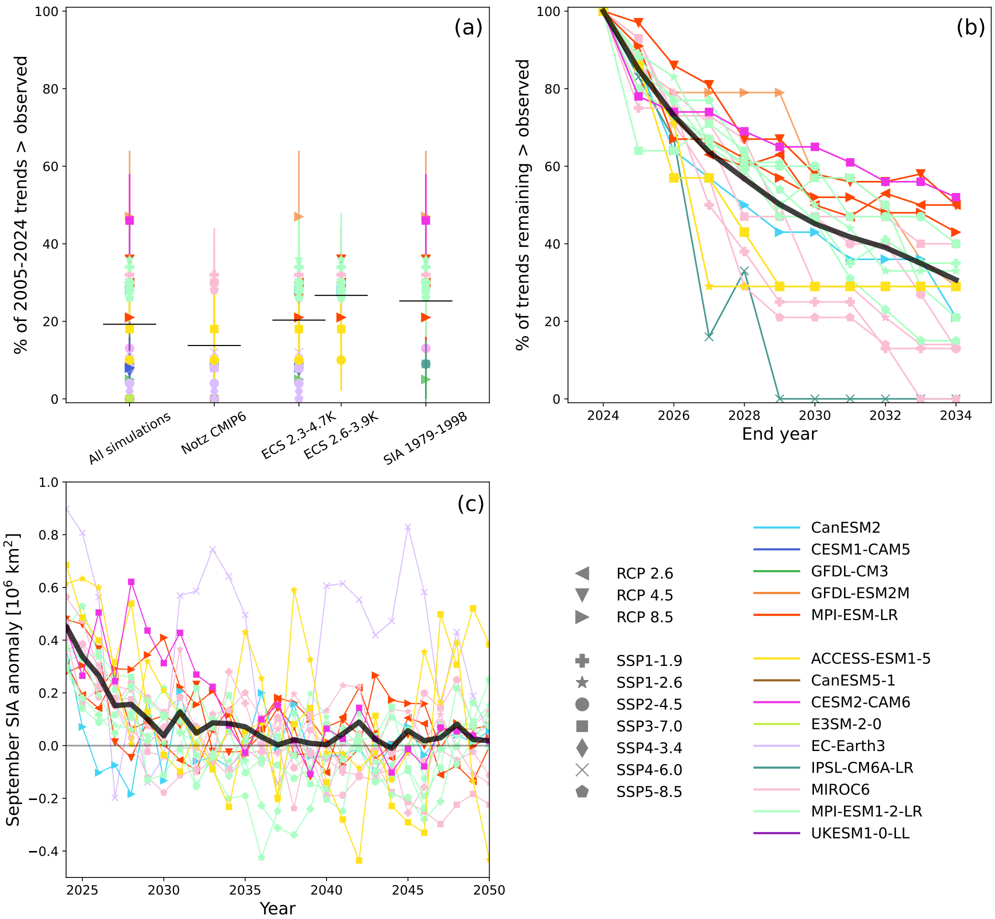

Figure 2. (a) The percentage of ensemble members [%] for each ensemble that have 2005-2024 September sea ice area loss trends less than the observed value. The uncertainty estimate is calculated by monte carlo simulation with replacement. All simulations are shown on the left, with different selection criteria (that outlined in Notz and SIMIP Community (2020), the 5-95% and 66% range of ECS (Sherwood et al., 2020), and the climatological sea ice area applied on the right. (b) The conditional probability across each ensemble for the trends starting in 2005 to continue to be above -0.29 10^6 km^2/decade for a given end year. (c) The ensemble-mean difference in September sea ice area [10^6 km^2] between ensemble members with and without ice loss pauses over 2005-2024 for the period 2025-2050. For panels (b) and (c) only models and scenarios with at least five members with 2005-2024 trends above observed were included, with the black line shows the weighted average according to Equation 1. In all panels, each colour represents a model and each symbol represents a different forcing scenario.

Taken together, the wealth of available CMIP5 and CMIP6 simulations suggest it is possible, perhaps even likely, that the present slowdown in sea ice decline may continue for a further 5-10 years. If that were the case it may then imply the occurrence of an early ice-free Arctic is less likely than raw model output would suggest (Jahn et al., 2016; Arthun et al., 2020; Wang et al., 2021; England & Polvani, 2023; Jahn et al., 2024).

3.4 Climate models suggest an important role for climate variability

Whether the present slowdown persists in the future or not, one final question remains to be answered: is the recent pause a response to anthropogenic forcings alone, or is there an important role for internal climate variability? When attempting to isolate the forced component of any observed trend from internal variability, it is important to keep in mind that - assuming the model simulations faithfully capture a plausible reality - the observations are expected to have the same broad features as individual ensemble members, i.e. that they are a combination of a forced trend plus one particular realization of internal variability (although one doesn't expect the observations to precisely match any one member). Given the well-established importance of internal climate variability in Arctic sea ice trends (Kay et al., 2011; Swart et al., 2015; England et al., 2019; Dörr et al., 2023), we next assess whether a change in the forced response could also be substantially contributing to the observed slowdown in ice loss.

First, we show the forced September sea ice loss for the period 2005-2024 as estimated by the linear trend of the ensemble mean for each model and scenario (Fig. 3, horizontal axis). We find there are only two model/scenario combinations (GFDL-ESM2M RCP8.5 and CESM2 SSP3-7.0) for which the forced trend is estimated to entirely explain observed trends in ice loss (shown in Fig. 3, as grey vertical lines) with minimal role for internal variability. Over 85% of the models we analyse here have a larger forced sea ice loss for this period than observed (as they lie to the left of the observed trends), implying that internal variability has acted to reduce the pace of ice loss.

Second, we ask: is there evidence that the forced response itself is slowing down relative to the previous two decades? On the vertical axis of Figure 3, therefore, we plot the ratio of the 2005-2024 forced trend to that of the preceding twenty years, 1986-2005, for each model and scenario combination: a ratio of 1.0 indicates no change in the pace of ice loss, > 1 indicates an acceleration and < 1 indicates a deceleration. Again we find that only GFDL-ESM2M RCP8.5 and CESM2 SSP3-7.0 suggest that the reduction in the forced trends accounts entirely for the observed slowdown. While the results from all the other models agree that this observed pause is not entirely a forced response, the remaining models are relatively evenly split (Fig. 3): roughly half the models suggest that the forced sea ice loss trend has modestly decelerated over the past two decades relative to the prior two decades, and roughly half suggest it has modestly accelerated (this is especially clear if we disregard the models which are unable to capture the observed recent trends).

In summary then: while the modelling evidence is uncertain as to whether anthropogenic forcings - even in part - for the recent slowdown in Arctic sea ice loss, it is very likely that internal climate variability is contributing to the slowdown in an important way.

4 Conclusion and Discussion

It is perhaps surprising that while global temperatures have risen rapidly, reaching record levels in the last few years, Arctic sea ice cover has shown no statistically significant decline over the past two decades. Nonetheless, analyzing two observational datasets and thousands of simulations from the CMIP5 and CMIP6 archives, we have established the following facts, which address the four questions raised in the introduction:

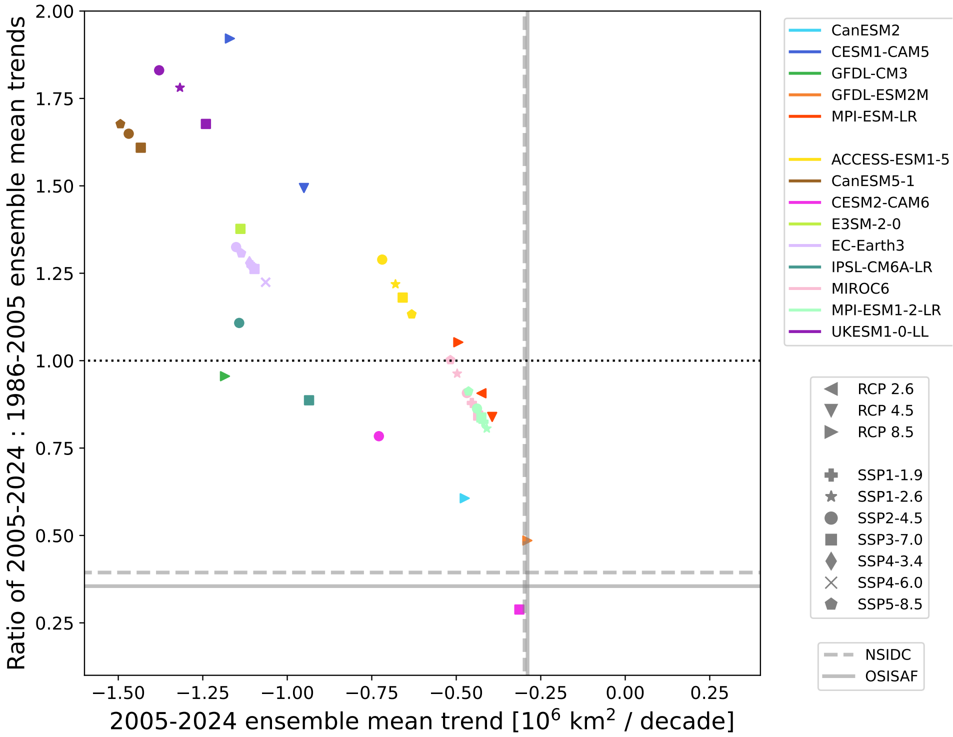

Figure 3. The ensemble mean trend in September sea ice area for the period 2005-2024 for each model and scenario (horizontal axis) versus the ratio of ensemble mean trends in September sea ice area for the periods 2005-2024 : 1986-2005 (vertical axis) with the black dotted line indicating a ratio of 1.0. Observational estimates of the 2005-2024 trend and the ratio of 2005-2024 : 1986-2005 trends are shown as grey lines (dashed line for NSIDC, solid line for OSISAF). Note that this does not imply that the observed trends are estimates of the forced response in the real climate system.

1. The pervasive slowdown of Arctic sea ice loss is robust across the choice of definitions, observational dataset, and season.
2. This observed pause in ice loss is simulated relatively frequently (with a 20% chance) in climate models, and is thus to be expected even under high emission scenarios.
3. If model simulations are accurate, the recent pause may plausibly continue for an additional five to ten years
4. Nearly all models analysed suggest an important role for internal climate variability in slowing the anthropogenically-forced sea ice loss.

We now return to the question of the contribution of human influence versus internal climate variability. If the slowdown is in fact a predominantly anthropogenically forced episode, our results suggest that there must be either some shared missing forcing or common model deficiency in response to the standard forcing among the majority of the models. While the latter part is difficult to assess, one culprit for a missing forcing could be the increase in boreal forest fires, not incorporated in standard scenarios. The recent study of Blanchard-Wrigglesworth et al. (2025) shows that incorporating recent biomass burning emissions into the CESM2 model leads to a rapid recovery of September sea ice cover during the period of interest due to increased reflection in the Northern Hemisphere of incoming shortwave radiation arising from the cloud response and aerosol cloud interactions. However, due to specifics of the simulation of polar clouds in CESM2 (DeRepentigny et al., 2022; Zhu et al., 2022; Davis & Medeiros, 2024; England & Feldl, 2024), and a seemingly opposite result from similar experiments with a different climate model (Zhong et al., 2024), further experiments with a wider range of models are needed to understand the role changes in biomass burning have had on observed Arctic sea ice trends.

Going forward, how can we use what we have learned about the recent pause in Arctic sea ice loss? Firstly, if internal variability has played an important role then this could provide a source of future predictability of Arctic climate change in the same manner as Yeager et al. (2015). And second, this period could be used as an out of sample test in future climate model evaluation – similar to the early and middle periods of the 20th century (Flynn et al., 2023; Bianco et al., 2024; Chen & Dai, 2024). However, overall this study is a reminder that we should be humble about multi-decadal predictions of the climate system, especially in highly variable regions such as the Arctic. Standing in 2007 or 2012 after having experienced another year of record loss and listening to assessments that climate models are flawed in their ability to reproduce the rapid loss of Arctic sea ice (Stroeve et al., 2007), it would take a rather brave person to have predicted that a sustained slowdown in ice loss was around the corner, although, as we have shown, and many have found before (Kay et al., 2011; Swart et al., 2015; R. Zhang, 2015), this is entirely consistent with what climate models simulate.

Open Research Section

All CMIP5 and CMIP6 data analysed in this study is publicly available to download from the Earth System Federation Grid at https://aims2.llnl.gov/search.

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References

Arthun, M., Onarheim, I., Dörr, J., & Eldevik, T. (2020). The seasonal and regional transition to an ice-free Arctic. *Geophysical Research Letters*, *48*(e2020GL090825). doi: 10.1029/2020GL0909825

Baxter, I., Ding, Q., Schweiger, A., L'Heureux, M., Baxter, S., Wang, T., ... Lu, J. (2019). How tropical Pacific surface cooling contributed to accelerated sea ice melt from 2007 to 2012 as ice is thinned by anthropogenic forcing. *Journal of Climate*, *32*, 8583-8602. doi: 10.1175/JCLI-D-18-0783.1

Bianco, E., Blanchard-Wrigglesworth, E., Materia, S., Ruggieri, P., Iovino, D., & Masina, S. (2024). CMIP6 models underestimate Arctic sea ice loss during the early twentieth-century warming, despite simulating large low-frequency sea ice variability. *Journal of Climate*, *37*, 6305-6321. doi: 10.1175/JCLI-D-23-0647.1

Blanchard-Wrigglesworth, E., DeRepentigny, P., & Frierson, D. (2025). Increasing boreal fires reduce future global warming and sea ice loss. *Preprint*. doi: 10.21203/rs.3.rs-5486231/v2

Chen, X., & Dai, A. (2024). Quantifying contributions of external forcing and internal variability to Arctic warming during 1900-2021. *Earth's Future*, *12*(e2023EF003734). doi: 10.1029/2023EF003734

Copernicus, E. (2024, April). *Climate indicators.* Retrieved 16/02/2025, from `https://climate.copernicus.eu/climate-indicators`

Davis, I., & Medeiros, B. (2024). Assessing CESM2 clouds and their response to climate change using cloud regimes. *Journal of Climate*, *37*, 2965-2985. doi: 10.1175/JCLI-D-23-0337.1

DeRepentigny, P., Jahn, A., Holland, M., Kay, J., Fasullo, J., Lamarque, J., ... Barrett, A. (2022). Enhanced simulated early 21st century Arctic sea ice loss due to CMIP6 biomass burning emissions. *Science Advances*, *8*(30). doi: 10.1126/sciadv.abo2405

Deser, C., & Phillips, A. (2021). Defining the internal component of Atlantic Multidecadal Variability in a changing climate. *Geophysical Research Letters*, *48*(e2021GL095023). doi: 10.1029/2021GL095023

Ding, Q., Schweiger, A., L'Heureux, M., Steig, E., Battisti, D., Johnson, N., ... Baxter, I. (2018). Fingerprints of internal drivers of Arctic sea ice loss in observations and model simulations. *Nature Geoscience*, *12*, 28-33. doi: 10.1038/s41561-018-0256-8

Dörr, J., Bonan, D., Arthun, M., Svendsen, L., & Wills, R. (2023). Forced and internal components of observed Arctic sea-ice changes. *The Cryosphere*, *17*, 4133-4153. doi: 10.5194/tc-17-4133-2023

England, M. (2021). Are multi-decadal fluctuations in arctic and antarctic surface temperatures a forced response to anthropogenic emissions or part of internal climate variability? *Geophysical Research Letters*, *48*(e2020GL090631). doi: 10.1029/2020GL090631

England, M., Eisenman, I., Lutsko, N., & Wagner, T. (2021). The recent emergence of Arctic Amplification. *Geophysical Research Letters*, *48*(e2021GL094086). doi: 10.1029/2021GL094086

England, M., & Feldl, N. (2024). Robust polar amplification in ice-free climates relies on ocean heat transport and cloud radiative effects. *Journal of Climate*, *37*, 2179-2197. doi: 10.1175/JCLI-D-23-0151.1

England, M., Jahn, A., & Polvani, L. (2019). Nonuniform contribution of internal variability to recent Arctic sea ice loss. *Journal of Climate*, *32*, 4039-4053. doi: 10.1175/JCLI-D-18-0864.1

England, M., & Polvani, L. (2023). The Montreal Protocol is delaying the occurrence of the first ice-free Arctic summer. *PNAS*, *120*(e2211432120). doi: 10.1073/pnas.2211432120

Fetterer, F., Knowles, K., Meier, W., Savoie, M., & Windnagel, A. (2017). *Sea ice index. (g02135, version 3).* [dataset]. National Snow and Ice Data Center. doi: 10.7265/N5K072F8

Flynn, C., Huusko, L., Modak, A., & Mauritsen, T. (2023). Strong aerosol cooling alone does not explain cold-biased mid-century temperatures in CMIP6 models. *Atmospheric Chemistry and Physics*, *23*, 15,121-15,133. doi: 10.5194/acp-23-15121-2023

Francis, J., & Wu, B. (2020). Why has no new record-minimum Arctic sea-ice extent occurred since september 2012? *Environmental Research Letters*, *15*(114034). doi: 10.1088/1748-9326/abc047

Fyfe, J., von Salzen, K., Gillett, N., Arora, V., Flato, G., & McConnell, J. (2013). One hundred years of Arctic surface temperature variation due to anthropogenic influence. *Scientific Reports*, *3*(2645). doi: 10.1038/srep02645

Gagne, M., Fyfe, J., Gillett, N., Polyakov, I., & Flato, G. (2017). Aerosol-driven increase in Arctic sea ice over the middle of the twentieth century. *Geophysical Research Letters*, *44*, 7338-7346. doi: 10.1002/2016GL071941

Hansen, J., Kharecha, P., Sato, M., Tselioudis, G., Kelly, J., Bauer, S., … Pokela, A. (2025). Global warming has accelerated: Are the United Nations and the public well-informed? *Environment: Science and Policy for Sustainable Development*, *67*, 6-44. doi: 10.1080/00139157.2025.2434494

IPCC. (2021). Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the Intergovernmental Panel on Climate Change. In V. Masson-Delmotte et al. (Eds.), (p. 3-32). Cambridge University Press.

Jahn, A., Holland, M., & Kay, J. (2024). Projections of an ice-free Arctic Ocean. *Nature Reviews Earth and Environment*, *5*, 167-176. doi: 10.1038/s43017-023-00515-9

Jahn, A., Kay, J., Holland, M., & Hall, D. (2016). How predictable is the timing of a summer ice-free Arctic? *Geophysical Research Letters*, *43*, 9113-9120. doi: 10.1002/2016GL070067

Kay, J., Holland, M., & Jahn, A. (2011). Inter-annual to multi-decadal Arctic sea ice extent trends in a warming world. *Geophysical Research Letters*, *38*(L15708). doi: 10.1029/2011GL048008

Kerr, R. (2000). A North Atlantic climate pacemaker for the centuries. *Science*, *288*, 1984-1985. doi: 10.1126/science.288.5473.1984

Kwok, R. (2018). Arctic sea ice thickness, volume, and multiyear ice coverage: losses and coupled variability (1958–2018). *Environmental Research Letters*, *13*, 105005. doi: 10.1088/1748-9326/aae3ec

Lee, Y., & Liu, W. (2023). The weakened Atlantic Meridional Overturning Circulation diminishes recent Arctic sea ice loss. *Geophysical Research Letters*, *50*(e2023GL105929). doi: 10.1029/2023GL105929

Lund, M., Myhre, G., & Samset, B. (2019). Anthropogenic aerosol forcing under the Shared Socioeconomic Pathways. *Atmospheric Chemistry and Physics*, *19*, 13827-13839. doi: 10.5194/acp-19-13827-2019

Manshausen, P., Watson-Parris, D., Christensen, M., Jalkanen, J., & Stier, P. (2022). Invisible ship tracks show large cloud sensitivity to aerosol. *Nature*, *610*, 101–106. doi: 10.1038/s41586-022-05122-0

Mantua, N., & Hare, S. (2002). The Pacific Decadal Oscillation. *Journal of Oceanography*, *58*, 35-44. doi: 10.1023/A:1015820616384

Maslowski, W., Kinney, J., Higgins, M., & Roberts, A. (2012). The future of Arctic sea ice. *Annual Review of Earth and Planetary Sciences*, *40*, 625-654. doi: 10.1146/annurev-earth-042711-105345

Meehl, G., Chung, C., Arblaster, J., Holland, M., & Bitz, C. (2018). Tropical decadal variability and the rate of Arctic sea ice decrease. *Geophysical Research Letters*, *45*, 11,326-11,333. doi: 10.1029/2018GL079989

Meehl, G., Senior, C., Eyring, V., Lamarque, J., Stouffer, R., Taylor, K., & Schlund, M. (2020). Context for interpreting equilibrium climate sensitivity and transient climate response from the CMIP6 Earth system models. *Science Advances*, *6*(eaba1981). doi: 10.1126/sciadv.aba1981

Meier, W., & Stewart, J. (2019). Assessing uncertainties in sea ice extent climate indicators. *Environmental Research Letters*, *14*(035005). doi: 10.1088/1748-9326/aaf52c

Merchant, C., Allan, R., & Embury, O. (2025). Quantifying the acceleration of multidecadal global sea surface warming driven by Earth's energy imbalance. *Environmental Research Letters*, *20*(024037). doi: 10.1088/1748-9326/adaa8a

Nafaji, M., Zwiers, F., & Gillett, N. (2015). Attribution of Arctic temperature change to greenhouse-gas and aerosol influences. *Nature Climate Change*, *5*, 246-249. doi: 10.1038/nclimate2524

Notz, D., & SIMIP Community. (2020). Arctic sea ice in CMIP6. *Geophysical Research Letters*, *47*(e2019GL086749). doi: 10.1029/2019GL086749

Notz, D., & Stroeve, J. (2016). Observed Arctic sea-ice loss directly follows anthropogenic CO2 emission. *Science*, *354*, 747-750. doi: 10.1126/science.aag2345

Onarheim, I., Arthun, M., Teigen, S., Eik, K., & Steele, M. (2024). Recent thickening of the Barents Sea ice cover. *Geophysical Research Letters*, *51*(e2024GL108225). doi: 10.1029/2024GL108225

OSI-420. (2023). *Osi saf sea ice index 1978-onwards, version 2.2.* [dataset]. EUMETSAT Ocean and Sea Ice Satellite Application Facility. doi: 10.15770/EUM_SAF_OSI_0022

Parkinson, C., & Comiso, J. (2013). On the 2012 record low Arctic sea ice cover: Combined impact of preconditioning and an August storm. *Geophysical Research Letters*, *40*, 1356-1361. doi: 10.1002/grl.50349

Rantanen, M., Karpechko, A., Lipponen, A., Hyvarinen, O., Ruosteenoja, K., Vihma, T., & Laaksonen, A. (2022). The Arctic has warmed nearly four times faster than the globe since 1979. *Communications Earth and Environment*, *3*(168). doi: 10.1038/s43247-022-00498-3

Samset, B., Zhou, C., Fuglestvedt, J., Lund, M., Marotzke, J., & Zelinka, M. (2023). Steady global surface warming from 1973 to 2022 but increased warming rate after 1990. *Communications Earth and Environment*, *4*(400). doi: 10.1038/s43247-023-01061-4

Schweiger, A., Lindsay, R., Zhang, J., Steele, M., Stern, H., & Kwok, R. (2011). Uncertainty in modeled Arctic sea ice volume. *Journal of Geophysical Research*, *116*(C00D06). doi: 10.1029/2011JC007084

Shen, Z., Duan, A., Zhou, W., Peng, Y., & Li, J. (2024). Reconciling roles of external forcing and internal variability in Arctic sea ice change on different time scales. *Journal of Climate*, *37*, 3577-3591. doi: 10.1175/JCLI-D-23-0280.1

Sherwood, S., Webb, M., Annan, J., Armour, K., Forster, P., Hargreaves, J., ... Zelinka, M. (2020). An assessment of Earth's climate sensitivity using multiple lines of evidence. *Review of Geophysics*, *58*(e2019RG000678). doi: 10.1029/2019RG000678

Siew, P., Wu, Y., Ting, M., Zheng, C., Ding, Q., & Seager, R. (2024). Significant contribution of internal variability to recent Barents–Kara sea ice loss in winter. *Communications Earth and Environment*, *5*(411). doi: 10.1038/s43247-024-01582-6

Stroeve, J., Holland, M., Meier, W., Scambos, T., & Serreze, M. (2007). Arctic sea ice decline: faster than forecast. *Geophysical Research Letters*, *34*(L09501). doi: 10.1029/2007GL029703

Stroeve, J., & Notz, D. (2018). Changing state of Arctic sea ice across all seasons. *Environmental Research Letters*, *13*(103001). doi: 10.1088/1748-9326/aade56

Stroeve, J., Serreze, M., Drobot, S., Gearhead, S., Holland, M., Maslanika, J., ... Scambos, T. (2011). Arctic sea ice extent plummets in 2007. *Eos*, *89*, 13-14.

doi: 10.1029/2008EO020001

Swart, N., Fyfe, J., Hawkins, E., Kay, J., & Jahn, A. (2015). Influence of internal variability on arctic sea-ice trends. *Nature Climate Change*, *5*, 86-89. doi: 10.1038/nclimate2483

Szopa, S., Balkanski, Y., Schulz, M., Bekki, S., Cugnet, D., Fortems-Cheiney, A., … Dufresne, J. (2013). Aerosol and ozone changes as forcing for climate evolution between 1850 and 2100. *Climate Dynamics*, *40*, 2223-2250. doi: 10.1007/s00382-012-1408-y

Wadhams, P. (2016). *A farewell to ice*. Penguin Publishing.

Walsh, J., Fetterer, F., Scott, J., & Chapman, W. (2017). A database for depicting Arctic sea ice variations back to 1850. *Geographical Review*, *107*, 89-107. doi: 10.1111/j.1931-0846.2016.12195.x

Wang, B., Zhou, X., Ding, Q., & Liu, J. (2021). Increasing confidence in projecting the Arctic ice-free year with emergent constraints. *Environmental Research Letters*, *16*(094016). doi: 10.1088/1748-9326/ac0b17

Yeager, S., Karspeck, A., & Danabasoglu, G. (2015). Predicted slowdown in the rate of Atlantic sea ice loss. *Geophysical Research Letters*, *42*, 10,704-10,713. doi: 10.1002/2015GL065364

Yoshioka, M., Grosvenor, D., Booth, B., Morice, C., & Carslaw, K. (2024). Warming effects of reduced sulfur emissions from shipping. *Atmospheric Chemistry and Physics*, *24*, 13681–13692. doi: 10.5194/acp-24-13681-2024

Zhang, J. (2021). Recent slowdown in the decline of Arctic sea ice volume under increasingly warm atmospheric and oceanic conditions. *Geophysical Research Letters*, *48*(e2021GL094780). doi: 10.1029/2021GL094780

Zhang, J., Lindsay, R., Schweiger, A., & Steele, M. (2013). The impact of an intense summer cyclone on 2012 Arctic sea ice retreat. *Geophysical Research Letters*, *40*, 720-726. doi: 10.1002/grl.50190

Zhang, R. (2015). Mechanisms for low-frequency variability of summer Arctic sea ice extent. *PNAS*, *112*, 4570-4575. doi: 10.1073/pnas.1422296112

Zhong, Q., Shutgens, N., Veraverbeke, S., & van der Werf, G. (2024). Increasing aerosol emissions from boreal biomass burning exacerbate Arctic warming. *Nature Climate Change*, *14*, 1275-1281. doi: 10.1038/s41558-024-02176-y

Zhu, J., Otto-Bliesner, B., Brady, E., Gettelman, A., Bacmeister, J., Neale, R., … Kay, J. (2022). LGM paleoclimate constraints inform cloud parameterizations and equilibrium climate sensitivity in CESM2. *Journal of Advances in Modeling Earth Systems*, *14*(e2021MS002776). doi: 10.1029/2021MS002776

Supporting Information for "Surprising, but not unexpected, multi-decadal pause in Arctic sea ice loss"

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Boucher, O., Servonnat, J., & co-authors. (2020). Presentation and evaluation of the IPSL-CM6A-LR climate model. *Journal of Advances in Modeling Earth Systems*, *12*(e2019MS002010). doi: 10.1029/2019MS002010

Burger, F., Terhaar, J., & Frölicher, T. (2022). Compound marine heatwaves and ocean acidity extremes. *Nature Communications*, *13*(4722). doi: 10.1038/s41467-022-32120-7

Fasullo, J., Golaz, J., Caron, J., Rosenbloom, N., Meehl, G., Strand, W., ... Bartoletti, T. (2024). An overview of the E3SM version 2 Large Ensemble and a comparison to other E3SM and CESM Large Ensembles. *Earth System Dynamics*, *15*, 367-386. doi: 10.5194/esd-15-367-2024

Kay, J., Deser, C., Phillips, A., Mai, A., Hannay, C., Strand, G., ... Vertenstein, M. (2015). The Community Earth System Model (CESM Large Ensemble project: A community resource for studying climate change in the presence of internal climate variability. *Bulletin of the American Meteorological Society*, *96*, 1333-1349. doi: 10.1175/BAMS-D-13-00255.1

Kirchmeier-Young, M., Zwiers, F., & Gillett, N. (2017). Attribution of extreme events in Arctic sea ice extent. *Journal of Climate*, *30*, 553-571. doi: 10.1175/JCLI-D-16-0412.1

Maher, N., Milinski, S., Suarez-Gutierrez, L., Botzet, M., Kornblueh, L., Kroger, J., ... Marotzke, J. (2019). The Max Planck Institute Grand Ensemble: Enabling the exploration of climate system variability. *Journal of Advances in Modeling Earth Systems*, *11*, 2050-2069. doi: 10.1029/2019MS001639

Olonscheck, D., Suarez-Gutierrez, L., Milinski, S., Beobide-Arsuaga, G., Baerh, J., Frob, F., ... Brune, S. (2023). The new Max Planck Institute Grand Ensemble with CMIP6 forcing and high-frequency model output. *Journal of Advances in Modeling Earth Systems*, *15*(e2023MS003790). doi: 10.1029/2023MS003790

Rodgers, K., Lee, S., Rosenbloom, N., Timmermann, A., Danabasoglu, G., Deser, C., ... Yeager, S. (2021). Ubiquity of human-induced changes in climate variability. *Earth*

System Dynamics, *12*, 1393-1411. doi: 10.5194/esd-12-1393-2021

Sellar, A., Jones, C., & co-authors. (2019). UKESM1: Description and evaluation of the UK Earth System Model. *Journal of Advances in Modeling Earth Systems*, *11*, 4513-4558. doi: 10.1029/2019MS001739

Sun, L., Alexander, M., & Deser, C. (2018). Evolution of the global coupled climate response to Arctic sea ice loss during 1990-2090 and its contribution to climate change. *Journal of Climate*, *31*, 7823-7843. doi: 10.1175/JCLI-D-18-0134.1

Swart, N., Cole, J., Kharin, V., Lazare, M., Scinocca, J., Gillett, N., … Winter, B. (2019). The Canadian Earth System Model version 5 (CanESM5.0.3). *Geoscientific Model Development*, *12*, 4823-4873. doi: 10.5194/gmd-12-4823-2019

Tatebe, H., Ogura, T., Nitta, T., Komuro, Y., Ogochi, K., Takemura, T., … Kimoto, M. (2019). Description and basic evaluation of simulated mean state, internal variability, and climate sensitivity of MIROC6. *Geoscientific Model Development*, *12*, 2727-2765. doi: 10.5194/gmd-12-2727-2019

Wyser, K., Koenigz, T., Fladrich, U., Fuentes-Franco, R., Karami, M., & Kruschke, T. (2021). The SMHI Large Ensemble (SMHI-LENS) with EC-Earth3.3.1. *Geoscientific Model Development*, *14*, 4781-4796. doi: 10.5194/gmd-14-4781-2021

Ziehn, T., Chamberlain, M., Law, R., Lenton, A., Bodman, R., Dix, M., … Srbinovsky, J. (2020). The Australian Earth System Model: ACCESM-ESM1.5. *Journal of Southern Hemisphere Earth Systems Science*, *80*, 193-214. doi: 10.1071.ES19035

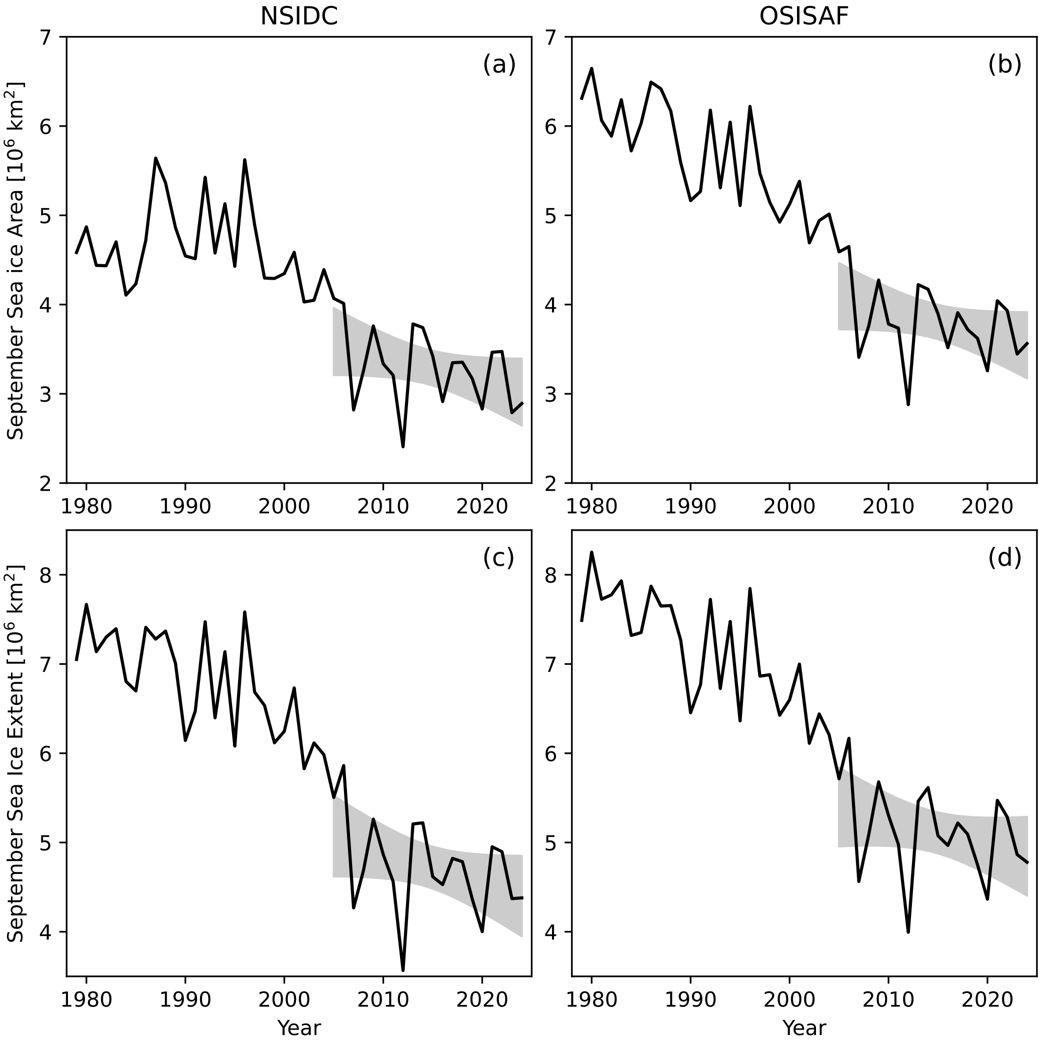

Figure S1. Timeseries of September sea ice area (top row) and sea ice extent (bottom row) for the NSIDC (left column) and OSISAF (right column) sea ice indices. The 95% confidence interval for the 20-year linear trend 2005-2024 is shown in the shading.

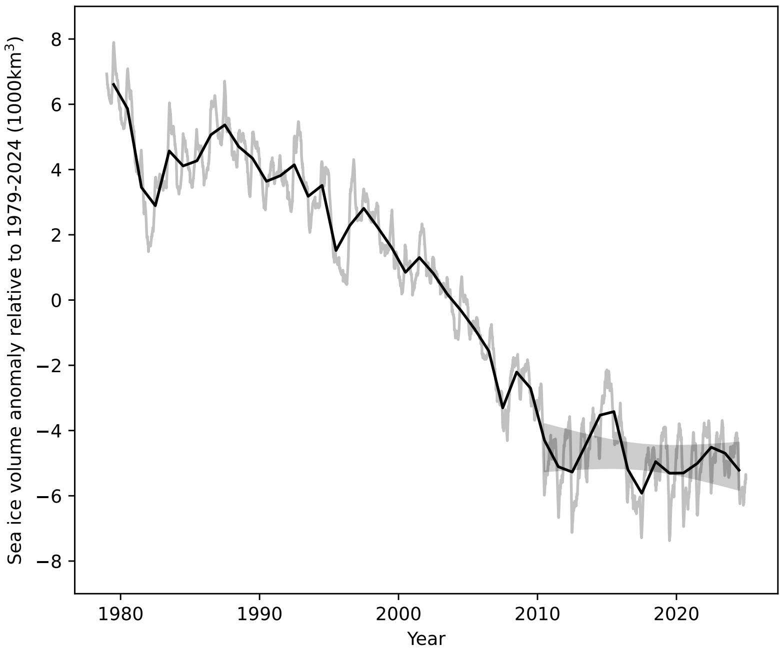

Figure S2. Timeseries of PIOMAS-simulated Arctic sea ice volume anomaly for the period 1979-2024. Anomalies are calculated as the departure from the long term 1979-2024 average, with daily anomalies shown in the grey and annual anomalies shown in the black. The 95% confidence interval for the 15-year linear trend 2010-2024 is shown in the shading.

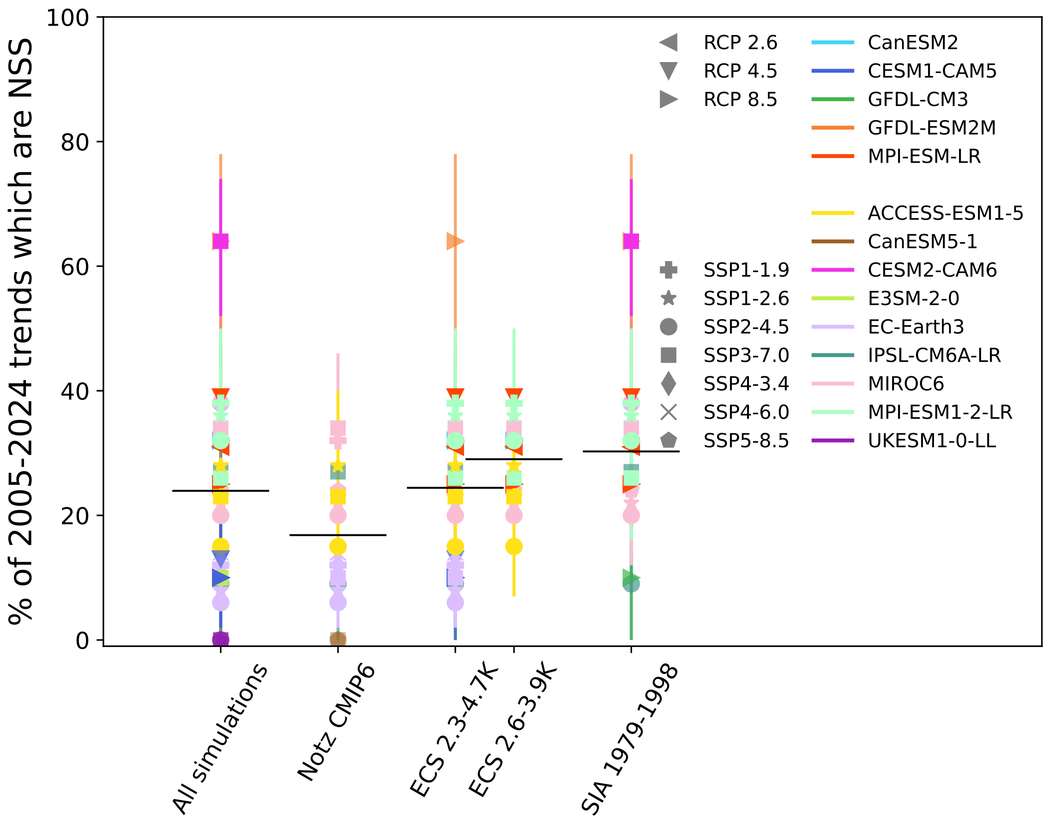

Figure S3. Same as in Figure 2 but for the percentage of members for which 2005-2024 September Arctic sea ice area trends are not statistically significant at 95% confidence.

Table S1. Details of the large ensemble simulations analysed in this study.

Model	Generation	Scenarios (members)	Reference
CESM1	CMIP5	RCP4.5 (15), RCP8.5 (40)	(Kay et al., 2015)
GFDL-CM3	CMIP5	RCP8.5 (20)	(Sun et al., 2018)
GFDL-ESM2M	CMIP5	RCP8.5 (30)	(Burger et al., 2022)
CanESM2	CMIP5	RCP8.5 (50)	(Kirchmeier-Young et al., 2017)
MPI-ESM-LR	CMIP5	RCP2.6, 4.5, and 8.5 (100)	(Maher et al., 2019)
ACCESS-ESM1-5	CMIP6	SSP1-2.6, 2-4.5, 3-7.0, and 5-8.5 (40)	(Ziehn et al., 2020)
CESM2	CMIP6	SSP2-4.5 (16), SSP3-7.0 (50[a])	(Rodgers et al., 2021)
CanESM5	CMIP6	SSP2-4.5, 3-7.0, and 5-8.5 (10)	(Swart et al., 2019)
EC-Earth 3	CMIP6	SSP1-1.9, 1-2.6, 2-4.5, 3-7.0, 4-3.4, 4-6.0, and 5-8.5 (50)	(Wyser et al., 2021)
IPSL CM6A	CMIP6	SSP2-4.5 and 3-7.0 (11)	(Boucher et al., 2020)
UKESM1-0-LL	CMIP6	SSP1-2.6 (16), SSP2-4.5 (15), SSP3-7.0 (16)	(Sellar et al., 2019)
MIROC6	CMIP6	SSP1-1.9, SSP1-2.6, 2-4.5, 3-7.0, and 5-8.5 (50)	(Tatebe et al., 2019)
MPI-ESM1.2	CMIP6	SSP1-1.9, 1-2.6, 2-4.5, 3-7.0, and 5-8.5 (50)	(Olonscheck et al., 2023)
E3SM-2-0	CMIP6	SSP3-7.0 (21)	(Fasullo et al., 2024)

[a] This is the members with or without biomass.