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Minimal Arctic Sea Ice Loss in the Last 20 Years, Consistent With Internal Climate Variability

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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

Supporting Information:

Supporting Information may be found in the online version of this article.

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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 data sets, metrics, and seasons. Large-ensemble CMIP5 and CMIP6 simulations reveal that such periods with minimal sea ice decline under increasing greenhouse gas emissions are not unusual. Analysis of ensemble members that simulate analogs of the observed pause indicates that the current slowdown could plausibly persist another five to 10 years, although the chances of a faster-than-average decline are increased in the near-future. The modeling evidence suggests that internal variability has substantially offset anthropogenically forced sea ice loss in recent decades. 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 modeling 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 it could plausibly continue for another five to 10 years, although the same slowdown makes a faster-than-average sea ice decline more likely in the coming 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 modeling 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 (Copernicus, 2024; IPCC, 2021). 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., 2008) and 2012 (Parkinson & Comiso, 2013; J. Zhang et al., 2013) fueled 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 (Hansen et al., 2025; Merchant et al., 2025; Samset et al., 2023). As Arctic sea ice cover is strongly tied to global temperatures (Mahlstein & Knutti, 2012; 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, a period of increasing anthropogenic greenhouse emissions without sustained sea ice loss—the mid-20th century (Walsh et al., 2017)—has already occurred. From the 1940s to the 1970s Arctic sea ice cover *expanded* (Gagne et al., 2017). 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 (England et al., 2021; Fyfe et al., 2013; Gagne et al., 2017; Nafaji et al., 2015); but these aerosol sources are far smaller today (Lund et al., 2019; Szopa et al., 2013) and a phase out of aerosol emissions from ship tracks have potentially contributed to enhanced global and Arctic warming since 2020 (Manshausen et al., 2022; Yoshioka et al., 2024). 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 (Dörr et al., 2023; England, 2021; England et al., 2019; Shen et al., 2024; Sweeney 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 reduction of sulfur 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 (Deser & Phillips, 2021; Kerr, 2000) and the Pacific Decadal Oscillation (Mantua & Hare, 2002), have an important imprint on Arctic sea ice. For example, variability emanating from the Pacific sector (Baxter et al., 2019; Ding et al., 2018) 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). Several recent studies (Dörr et al., 2023; Shen et al., 2024; Siew et al., 2024), based on different methods, 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 pervasive 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?

We would like to underscore that *pause* or *slowdown* are used interchangeably to refer to an extended period with little or no decline in sea ice cover, due to the observed realization of multi-decadal climate variability on top of the response to anthropogenic forcing, temporarily interrupting the ongoing long-term reduction in Arctic sea ice. This does not imply a cessation of human-induced climate change and, instead, it is likely that sea ice would have increased over this period without human influence.

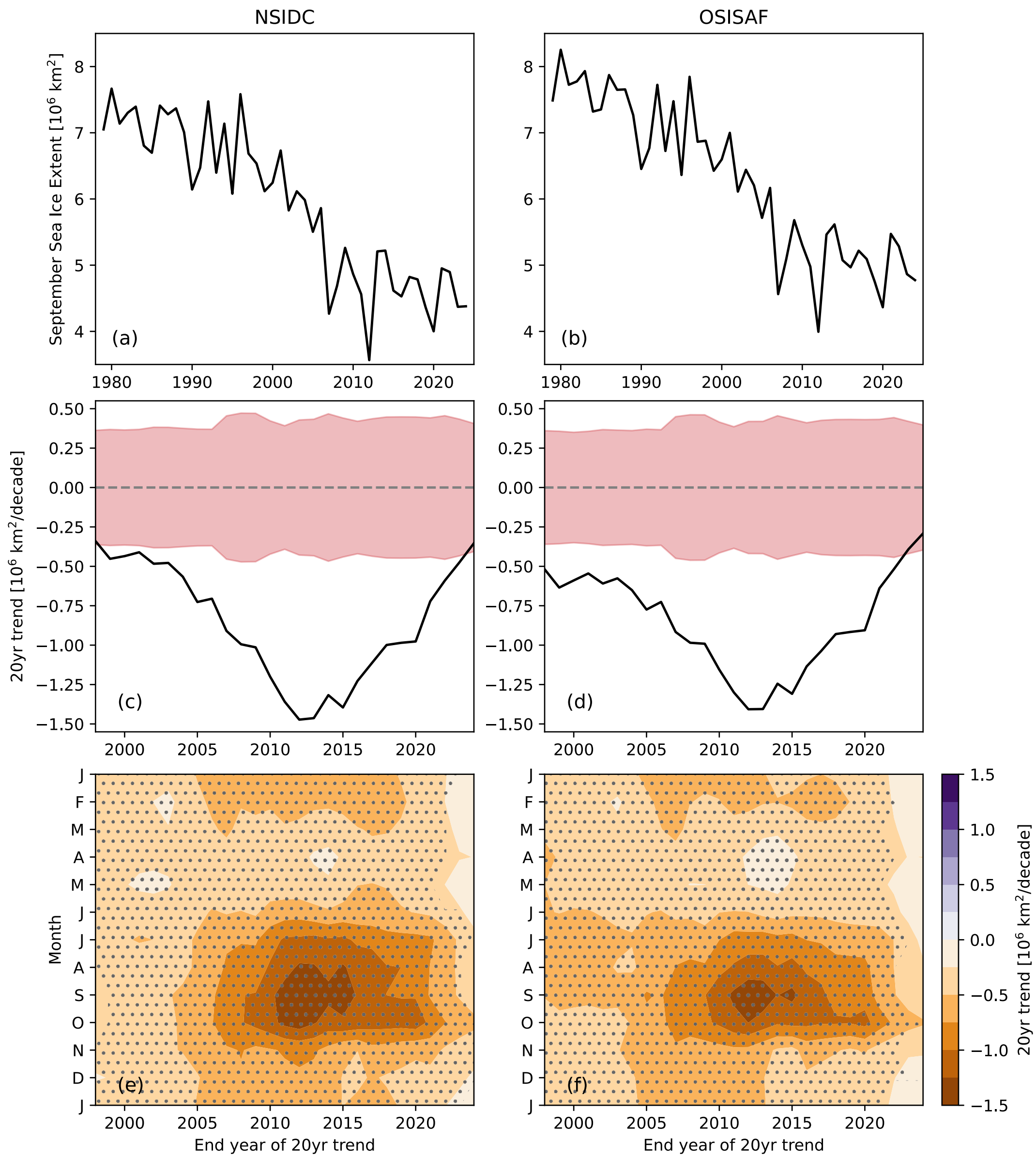

Figure 1. (a, b) Observed September sea ice extent [10^6 km^2] 1979–2024, (c, d) 20 year-trends of September sea ice extent [10^6 km^2/decade] with varying end year from 1998 to 2024, in which the red shaded envelope shows the bounds inside which a linear trend is not statistically significant according to a *t*-test at 95% confidence and (e, f) the 20 year-trends of sea ice extent with varying end years but for each month of the year, with stippling showing statistically significant declines at a 95% confidence level. 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).

2. Data and Methods

To investigate the evolution in Arctic sea ice cover, we utilize both the NSIDC (Fetterer et al., 2017) and the OSISAF (OSI-420, 2023) sea ice indices. Both are continually updated data records of the Arctic sea area and extent, for the period 1979–present, derived from satellite measurements. We focus on Arctic sea ice extent, due to discrepancies in the sea ice area between the two products at the start of the satellite record (Meier & Stewart, 2019), however we have also analyzed sea ice area and the main results of this paper are unchanged (Figures 1a and 1b and Figure S1 in Supporting Information S1). For understanding changes in the simulated Arctic sea ice volume we utilize 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 10 members is used, as summarized in Table S1 in Supporting Information 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 analyzing simulated changes in Arctic sea ice cover is to compute the linear trend for the 20-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 of 10–100 members to examine the spread of simulated trends for each model and scenario. The main definition of pause used in this study is motivated by the observed 2005–2024 September sea ice extent trends (>−0.29 million km^2/dec, taking the most conservative estimate from observations). 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 (see Supporting Information S1 for a detailed explanation).

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 extent for the most recent two decades 2005–2024 is −0.35 and −0.29 million km^2 per decade according to the NSIDC and OSISAF sea ice indices respectively (Figures 1a and 1b). 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 Figures 1c and 1d 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, and second slowest for the NSIDC record. For both data sets, this insignificant trend is four to five 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 (Figure S1 in Supporting Information 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 Figures 1e and 1f. 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. We speculate that a negative sea ice thickness feedback and changes in ocean heat transport convergence near the sea ice edge could play important roles (Bitz et al., 2005; Oldenburg et al., 2024; Polyakov et al., 2023; Sumata et al., 2023).

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 15 years (Figure S2 in Supporting Information S1), consistent with previous work (J. Zhang, 2021). 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 seven-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 is most evident in the Barents Sea (Onarheim et al., 2024).

Various aspects of this pause in Arctic sea ice loss have been documented in recent studies (Polyakov et al., 2023; Stern, 2025; Sumata et al., 2023), building a consistent picture of a thinner ice cover which has remained basically unchanged since the late 2000s. Altogether, strong observational evidence reveals 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, and 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; Lee & Liu, 2023; Swart et al., 2015), we find that nearly all models can 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 less sea ice loss than observed. The main result here is that the multi-model average suggests a nearly 20% chance of this pause in Arctic sea ice loss (Figure 2a, column 1). However, we note a large spread across the CMIP5 and CMIP6 models, with the probability of a smaller-than-observed 2005–2024 trend varying from 0% and approximately 40%.

The central estimated value of nearly 20% doesn't change substantially if models are selected following the criteria from Notz and SIMIP Community (2020), or according to their climate sensitivity (Sherwood et al., 2020), or using models according to their ability to simulate climatological sea ice conditions, or how sensitive they are to the biomass burning variability in the CMIP6 forcing (DeRepentigny et al., 2022) (Figure 2a, column 2–5). The central estimate is only slightly higher if we assess the probability of a non-statistically significant trend (Figure S3 in Supporting Information S1). 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, to the metric of interest, or to the choice of sea ice extent or area (compare Figure S4 in Supporting Information S1 and Figure 2). 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 minimal sea ice loss in the period from 2005 to 2024 (Figure 2a), and quantify how long the simulated slowdowns persist in the future (Figure 2b). The multi-model average suggests that pauses in September sea ice loss for the period 2005–2024 have a nearly 1 in 2 chance of persisting for a further 5 years, and a 1 in 4 chance of persisting for a further 10 years (note, however, the considerable intermodel spread of $\pm 25\%$). Higher emissions scenarios typically tend to show slightly lower probabilities of sustaining the muted pace of Arctic sea ice loss in the future.

On average, the sea ice extent in ensemble members which simulate pauses in sea ice loss for the period 2005–2024 is 0.6 million km^2 larger in 2025 than in ensemble members from the same models and scenarios in which there is no pause (Figure 2c). This source of predictability mostly decays within a decade in the multi-model mean, and after that the September sea ice area in ensemble members with and without pauses are indistinguishable from each other.

To ensure robust estimates, we included only models with at least five ensemble members simulating sea ice pauses during 2005–2024. This selection may bias our results toward models with larger ensembles or those more frequently simulating pauses. The probability of a sea ice loss pause in this subset, closer to 25%, is slightly higher than the estimate from all models. Thus, if the observed slowdown is in fact rare, our approach could overestimate its persistence. Nonetheless, over two-thirds of suitable models are included, and our findings align with previous research indicating that multi-decadal pauses in sea ice loss remain plausible in the late 21st century under medium emissions scenarios (Swart et al., 2015).

Whilst we have outlined the chance of the pause in sea ice loss persisting, all simulations suggest that sea ice conditions will inevitably revert back toward the longer term forced sea ice loss trend. In fact, there is substantial agreement among the model simulations that, for the five year period following the identified pause (2024–2028), members with pauses exhibit a more rapid loss of sea ice extent than members without pauses (comparing red and

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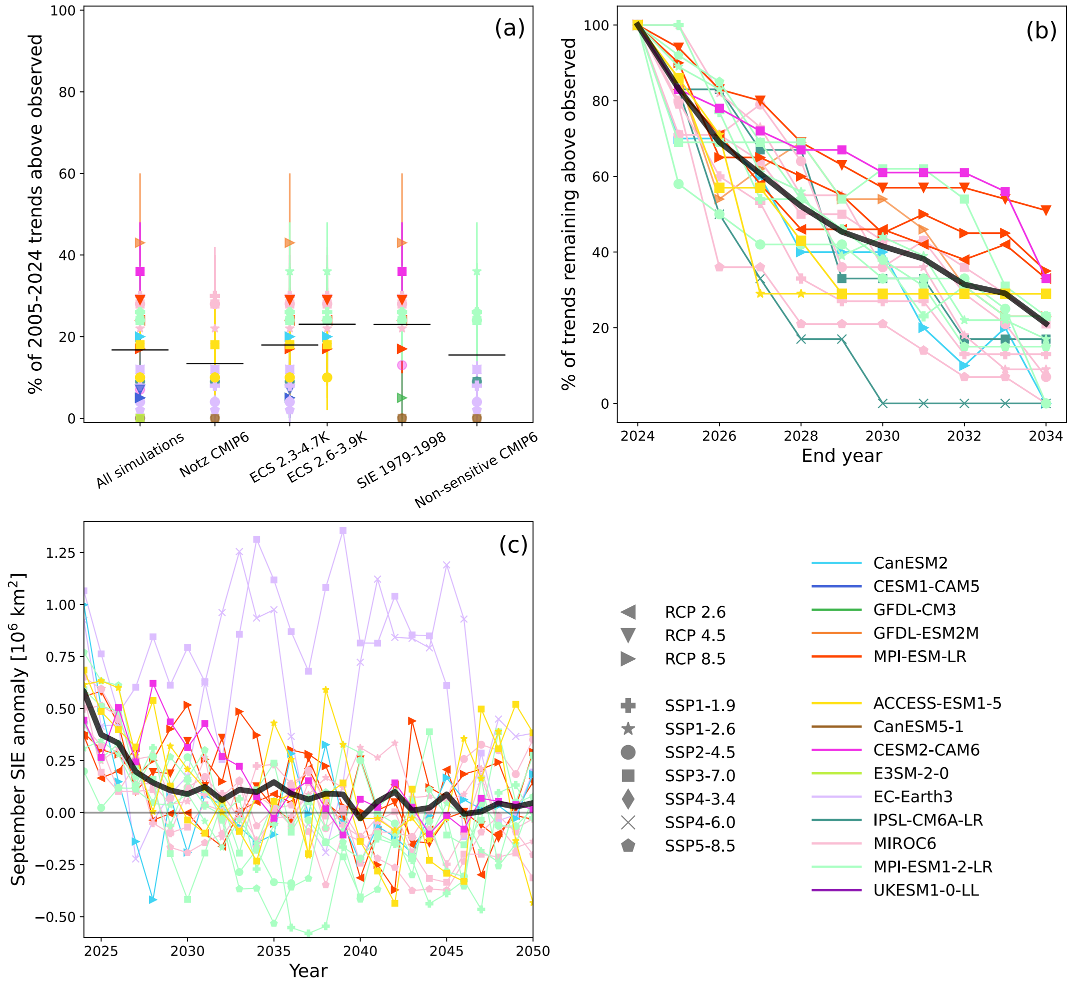

Figure 2. (a) The percentage of ensemble members [%] for each ensemble that have 2005–2024 September sea ice extent trends more positive than the observed value. The uncertainty estimate is calculated by Monte Carlo simulation with replacement. All simulations are shown on the left, with different selection criteria (that outlined in Notz and SIMIP Community (2020), the 5%–95% and 66% range of ECS (Sherwood et al., 2020), the climatological sea ice extent, and CMIP6 models identified as non-sensitive to biomass burning emissions by DeRepentigny et al. (2022)) applied on the right. (b) The conditional probability across each ensemble for the trends longer than 20 years 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 extent [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 S1 in Supporting Information S1. In all panels, each color represents a model and each symbol represents a different forcing scenario.

blue markers in Figure S5 in Supporting Information S1). The multi-model average indicates that sea ice loss could be 0.6 million km^2 per decade faster than the broader long-term decline.

Taken together, the wealth of available CMIP5 and CMIP6 simulations suggest it is possible that the present pause in sea ice decline may continue for a further 5–10 years, which would be consistent with timescales of Pacific ocean variability (Screen & Deser, 2019). 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 (Arthun et al., 2020; England & Polvani, 2023; Jahn et al., 2016, 2024; Wang et al., 2021). However, we find that the existence of this slowdown also predisposes the sea ice cover for a more rapid decline in the near future.

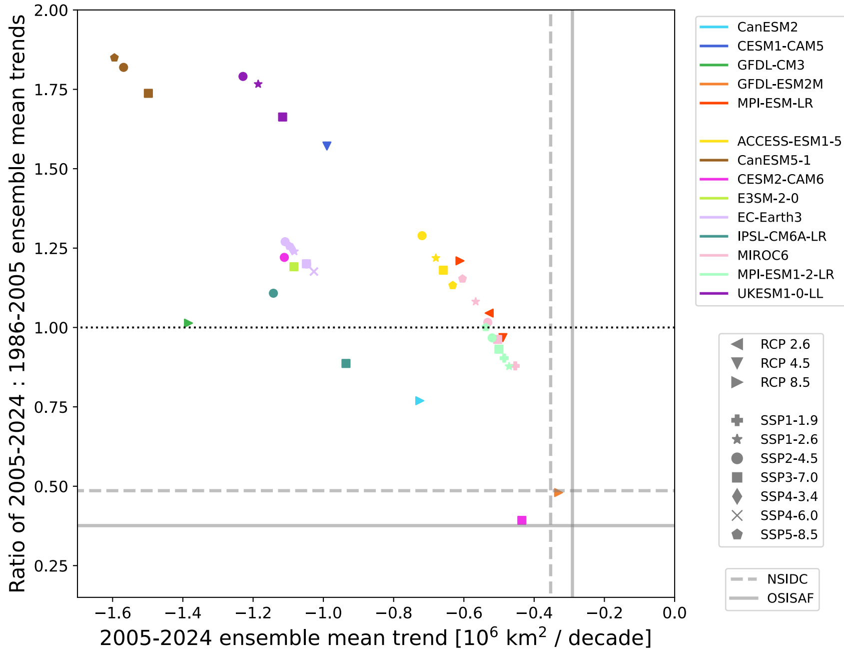

Figure 3. The ensemble mean trend in September sea ice extent for the period 2005–2024 for each model and scenario (horizontal axis) versus the ratio of ensemble mean trends in September sea ice extent for the periods 2005–2024:1986–2005 (vertical axis) with the black dotted line indicating a ratio of 1.0. Observational estimates of the 2005–2024 trend and the ratio of 2005–2024:1986–2005 trends are shown as gray 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.

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, that is 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 (Dörr et al., 2023; England et al., 2019; Kay et al., 2011; Swart et al., 2015), we next assess whether a change in the forced response could also be substantially contributing to the observed pause 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 (Figure 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 Figure 3, as gray vertical lines) with minimal role for internal variability. Over 85% of the models we analyze 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 20 years, 1986–2005, for each model and scenario combination: a ratio of 1 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 (Figure 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. Examining the ensemble mean sea ice cover in each model (Figure S6 in Supporting Information S1) confirms that most models show no discernible evidence for a forced slowdown over the last two decades.

In summary then: while the modeling evidence is uncertain as to whether anthropogenic forcings account—even in part—for the recent pause 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 data sets 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:

1. The pervasive slowdown of Arctic sea ice loss is robust across the choice of definitions, observational data set, and season.
2. This observed pause in ice loss is simulated relatively frequently (a nearly 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 10 years. However, this pause also heightens the risk of a more rapid decline in sea ice cover in the coming years.
4. Nearly all models analyzed suggest an important role for internal climate variability in slowing the anthropogenically-forced sea ice loss.

Returning to the relative contributions of human influence and internal variability, our results indicate that if the slowdown is in fact a predominantly anthropogenically forced episode there must be either some missing forcing or common model deficiency in response to known forcings. We find that the recovery of Arctic sea ice in CESM2 in response to the prescribed variability of biomass burning emissions (DeRepentigny et al., 2022; Fasullo et al., 2022) is not broadly replicated by other CMIP6 models (Figure S6 in Supporting Information S1) and so is unlikely to explain the current pause. One potential missing forcing is the increase in boreal forest fires, not incorporated in standard scenarios. The recent study of Blanchard-Wrigglesworth et al. (2025) finds that incorporating recent biomass burning emissions into CESM2 leads to a rapid recovery of September sea ice cover during the period of interest. However, due to specifics of the simulation of polar clouds in CESM2 (Davis & Medeiros, 2024; DeRepentigny et al., 2022; England & Feldl, 2024; Zhu et al., 2022), and a seemingly opposite result from similar experiments with a different 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? First, if internal variability has played an important role then the present slowdown could provide a source of future predictability of Arctic climate change in the same manner as Yeager et al. (2015) (see our Figure S5 in Supporting Information S1). Some studies (Stern, 2025; Sumata et al., 2023) have characterized this period as a regime shift in Arctic sea ice cover, which may also help to narrow sea ice trend projections. Second, the pause period could be used as an out of sample test in future climate model evaluation—like the early and middle periods of the 20th century (Bianco et al., 2024; Chen & Dai, 2024; Flynn et al., 2023). Nonetheless, the results of our study is a reminder that one needs to be cautious 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 yet 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 several studies have documented (Kay et al., 2011; Swart et al., 2015; R. Zhang, 2015), the current pause is entirely consistent with the state-of-the-art model simulations.

Data Availability Statement

All CMIP5 and CMIP6 data analyzed in this study is publicly available to download from the Earth System Federation Grid at https://aims2.llnl.gov/search. Sea ice observational products are available at the following addresses—NSIDC sea ice index https://nsidc.org/sea-ice-today/sea-ice-tools, OSISAF sea ice index https://osi-saf.eumetsat.int/products/osi-420 and PIOMAS sea ice volume anomaly data https://psc.apl.uw.edu/research/projects/arctic-sea-ice-volume-anomaly/data/.

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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. https://doi.org/10.1029/2020GL0909825

Baxter, I., Ding, Q., Schweiger, A., L'Heureux, M., Baxter, S., Wang, T., et al. (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*(24), 8583–8602. https://doi.org/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*(23), 6305–6321. https://doi.org/10.1175/JCLI-D-23-0647.1

Bitz, C., Holland, M., Hunke, E., & Moritz, R. (2005). Maintenance of the sea-ice edge. *Journal of Climate*, *18*(15), 2903–2921. https://doi.org/10.1175/JCLI3428.1

Blanchard-Wrigglesworth, E., DeRepentigny, P., & Frierson, D. (2025). Increasing boreal fires reduce future global warming and sea ice loss. *Proceedings of the National Academy of Sciences of the United States of America*, *122*(23), e2424614122. https://doi.org/10.1073/pnas.2424614122

Chen, X., & Dai, A. (2024). Quantifying contributions of external forcing and internal variability to Arctic warming during 1900-2021. *Earth's Future*, *12*(5), e2023EF003734. https://doi.org/10.1029/2023EF003734

Copernicus, E. (2024). Climate indicators. Retrieved 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*(10), 2965–2985. https://doi.org/10.1175/JCLI-D-23-0337.1

DeRepentigny, P., Jahn, A., Holland, M., Kay, J., Fasullo, J., Lamarque, J., et al. (2022). Enhanced simulated early 21st century Arctic sea ice loss due to CMIP6 biomass burning emissions. *Science Advances*, *8*(30). https://doi.org/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*(22), e2021GL095023. https://doi.org/10.1029/2021GL095023

Ding, Q., Schweiger, A., L'Heureux, M., Steig, E., Battisti, D., Johnson, N., et al. (2018). Fingerprints of internal drivers of Arctic sea ice loss in observations and model simulations. *Nature Geoscience*, *12*(1), 28–33. https://doi.org/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*(9), 4133–4153. https://doi.org/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*(6), e2020GL090631. https://doi.org/10.1029/2020GL090631

England, M., Eisenman, I., Lutsko, N., & Wagner, T. (2021). The recent emergence of Arctic Amplification. *Geophysical Research Letters*, *48*(15), e2021GL094086. https://doi.org/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*(7), 2179–2197. https://doi.org/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*(13), 4039–4053. https://doi.org/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. *Proceedings of the National Academy of Sciences of the United States of America*, *120*(22), e2211432120. https://doi.org/10.1073/pnas.2211432120

Fasullo, J., Lamarque, J., Hannay, C., Rosenbloom, N., Tilmes, S., DeRepentigny, P., et al. (2022). Spurious late historical-era warming in CESM2 driven by prescribed biomass burning emissions. *Geophysical Research Letters*, *49*(2), e2021GL097420. https://doi.org/10.1029/2021GL097420

Fetterer, F., Knowles, K., Meier, W., Savoie, M., & Windnagel, A. (2017). Sea ice index. (g02135, version 3) [Dataset]. *National Snow and Ice Data Center*. https://doi.org/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*, 15121–15133. https://doi.org/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*(11), 114034. https://doi.org/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*(1), 2645. https://doi.org/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*(14), 7338–7346. https://doi.org/10.1002/2016GL071941

Hansen, J., Kharecha, P., Sato, M., Tselioudis, G., Kelly, J., Bauer, S., et al. (2025). Global warming has accelerated: Are the United Nations and the public well-informed? *Environment: Science and Policy for Sustainable Development*, *67*(1), 6–44. https://doi.org/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* (pp. 3–32). Cambridge University Press.

Jahn, A., Holland, M., & Kay, J. (2024). Projections of an ice-free Arctic Ocean. *Nature Reviews Earth & Environment*, *5*(3), 167–176. https://doi.org/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*(17), 9113–9120. https://doi.org/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*(15), L15708. https://doi.org/10.1029/2011GL048008

Kerr, R. (2000). A North Atlantic climate pacemaker for the centuries. *Science*, *288*(5473), 1984–1985. https://doi.org/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*(10), 105005. https://doi.org/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*(21), e2023GL105929. https://doi.org/10.1029/2023GL105929

Lund, M., Myhre, G., & Samset, B. (2019). Anthropogenic aerosol forcing under the Shared Socioeconomic Pathways. *Atmospheric Chemistry and Physics*, *19*(22), 13827–13839. https://doi.org/10.5194/acp-19-13827-2019

Mahlstein, I., & Knutti, R. (2012). September Arctic sea ice predicted to disappear near 2C global warming above present. *Journal of Geophysical Research*, *117*(D6), D06104. https://doi.org/10.1029/2011JD016709

Manshausen, P., Watson-Parris, D., Christensen, M., Jalkanen, J., & Stier, P. (2022). Invisible ship tracks show large cloud sensitivity to aerosol. *Nature*, *610*(7930), 101–106. https://doi.org/10.1038/s41586-022-05122-0

Mantua, N., & Hare, S. (2002). The Pacific Decadal Oscillation. *Journal of Oceanography*, *58*(1), 35–44. https://doi.org/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*(1), 625–654. https://doi.org/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*(20), 11326–11333. https://doi.org/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*(26), eaba1981. https://doi.org/10.1126/sciadv.aba1981

Meier, W., & Stewart, J. (2019). Assessing uncertainties in sea ice extent climate indicators. *Environmental Research Letters*, *14*(3), 035005. https://doi.org/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*(2), 024037. https://doi.org/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*(3), 246–249. https://doi.org/10.1038/nclimate2524

Notz, D., & SIMIP Community. (2020). Arctic sea ice in CMIP6. *Geophysical Research Letters*, *47*(10), e2019GL086749. https://doi.org/10.1029/2019GL086749

Notz, D., & Stroeve, J. (2016). Observed Arctic sea-ice loss directly follows anthropogenic CO2 emission. *Science*, *354*(6313), 747–750. https://doi.org/10.1126/science.aag2345

Oldenburg, D., Kwon, Y., Frankignoul, C., Danabasoglu, G., Yeager, S., & Kim, W. (2024). The respective roles of ocean heat transport and surface heat fluxes in driving Arctic Ocean warming and sea ice decline. *Journal of Climate*, *37*(4), 1431–1448. https://doi.org/10.1175/JCLI-D-23-0399.1

Onarheim, I., Arthun, M., Teigen, S., Eik, K., & Steele, M. (2024). Recent thickening of the Barents Sea ice cover. *Geophysical Research Letters*, *51*(10), e2024GL108225. https://doi.org/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*. https://doi.org/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*(7), 1356–1361. https://doi.org/10.1002/grl.50349

Polyakov, I., Ingvaldsen, R., Pnyushkov, A., Bhatt, U., Francis, J., Janout, M., et al. (2023). Fluctuation Atlantic inflows module Arctic atlantification. *Science*, *381*(6661), 972–979. https://doi.org/10.1126/science.adh5158

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 & Environment*, *3*(168), 168. https://doi.org/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 & Environment*, *4*(1), 400. https://doi.org/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. https://doi.org/10.1029/2011JC007084

Screen, J., & Deser, C. (2019). Pacific ocean variability influences the time of emergence of a seasonally ice-free Arctic Ocean. *Geophysical Research Letters*, *46*(4), 2222–2231. https://doi.org/10.1029/2018GL081393

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*(13), 3577–3591. https://doi.org/10.1175/JCLI-D-23-0280.1

Sherwood, S., Webb, M., Annan, J., Armour, K., Forster, P., Hargreaves, J., et al. (2020). An assessment of Earth's climate sensitivity using multiple lines of evidence. *Review of Geophysics*, *58*(4), e2019RG000678. https://doi.org/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 & Environment*, *5*(1), 411. https://doi.org/10.1038/s43247-024-01582-6

Stern, H. (2025). Regime shift in Arctic Ocean sea-ice extent. *Geophysical Research Letters*, *52*(8), e2024GL114546. https://doi.org/10.1029/2024GL114546

Stroeve, J., Holland, M., Meier, W., Scambos, T., & Serreze, M. (2007). Arctic sea ice decline: Faster than forecast. *Geophysical Research Letters*, *34*(9), L09501. https://doi.org/10.1029/2007GL029703

Stroeve, J., & Notz, D. (2018). Changing state of Arctic sea ice across all seasons. *Environmental Research Letters*, *13*(10), 103001. https://doi.org/10.1088/1748-9326/aade56

Stroeve, J., Serreze, M., Drobot, S., Gearhead, S., Holland, M., Maslanika, J., et al. (2008). Arctic sea ice extent plummets in 2007. *Eos*, *89*(2), 13–14. https://doi.org/10.1029/2008EO020001

Sumata, H., de Steur, L., Divine, D., Granskog, M., & Gerland, S. (2023). Regime shift in Arctic Ocean sea ice thickness. *Nature*, *615*(7952), 443–449. https://doi.org/10.1038/s41586-022-05686-x

Swart, N., Fyfe, J., Hawkins, E., Kay, J., & Jahn, A. (2015). Influence of internal variability on arctic sea-ice trends. *Nature Climate Change*, *5*(2), 86–89. https://doi.org/10.1038/nclimate2483

Sweeney, A., Fu, Q., Po-Chedley, S., Wang, H., & Wang, M. (2024). Unique temperature trend pattern associated with internally driven global cooling and Arctic warming during 1980-2022. *Geophysical Research Letters*, *51*(11), e2024GL108798. https://doi.org/10.1029/2024GL108798

Szopa, S., Balkanski, Y., Schulz, M., Bekki, S., Cugnet, D., Fortems-Cheiney, A., et al. (2013). Aerosol and ozone changes as forcing for climate evolution between 1850 and 2100. *Climate Dynamics*, *40*(9–10), 2223–2250. https://doi.org/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*(1), 89–107. https://doi.org/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*(9), 094016. https://doi.org/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*(24), 10704–10713. https://doi.org/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*(23), 13681–13692. https://doi.org/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*(18), e2021GL094780. https://doi.org/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*(4), 720–726. https://doi.org/10.1002/grl.50190

Zhang, R. (2015). Mechanisms for low-frequency variability of summer Arctic sea ice extent. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(15), 4570–4575. https://doi.org/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*(12), 1275–1281. https://doi.org/10.1038/s41558-024-02176-y

Zhu, J., Otto-Bliesner, B., Brady, E., Gettelman, A., Bacmeister, J., Neale, R., et al. (2022). LGM paleoclimate constraints inform cloud parameterizations and equilibrium climate sensitivity in CESM2. *Journal of Advances in Modeling Earth Systems*, *14*(4), e2021MS002776. https://doi.org/10.1029/2021MS002776

References From the Supporting Information

Boucher, O., Servonnat, J., Albright, A. L., Aumont, O., Balkanski, Y., Bastrikov, V., et al. (2020). Presentation and evaluation of the IPSL-CM6A-LR climate model. *Journal of Advances in Modeling Earth Systems*, *12*(7), e2019MS002010. https://doi.org/10.1029/2019MS002010

Burger, F., Terhaar, J., & Frölicher, T. (2022). Compound marine heatwaves and ocean acidity extremes. *Nature Communications*, *13*(1), 4722. https://doi.org/10.1038/s41467-022-32120-7

Fasullo, J., Golaz, J., Caron, J., Rosenbloom, N., Meehl, G., Strand, W., et al. (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. https://doi.org/10.5194/esd-15-367-2024

Kay, J., Deser, C., Phillips, A., Mai, A., Hannay, C., Strand, G., et al. (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*(8), 1333–1349. https://doi.org/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*(2), 553–571. https://doi.org/10.1175/JCLI-D-16-0412.1

Maher, N., Milinski, S., Suarez-Gutierrez, L., Botzet, M., Kornblueh, L., Kroger, J., et al. (2019). The Max Planck Institute Grand Ensemble: Enabling the exploration of climate system variability. *Journal of Advances in Modeling Earth Systems*, *11*(7), 2050–2069. https://doi.org/10.1029/2019MS001639

Olonscheck, D., Suarez-Gutierrez, L., Milinski, S., Beobide-Arsuaga, G., Baerh, J., Frob, F., et al. (2023). The new Max Planck Institute Grand Ensemble with CMIP6 forcing and high-frequency model output. *Journal of Advances in Modeling Earth Systems*, *15*(10), e2023MS003790. https://doi.org/10.1029/2023MS003790

Rodgers, K., Lee, S., Rosenbloom, N., Timmermann, A., Danabasoglu, G., Deser, C., et al. (2021). Ubiquity of human-induced changes in climate variability. *Earth System Dynamics*, *12*(4), 1393–1411. https://doi.org/10.5194/esd-12-1393-2021

Sellar, A., Jones, C., Mulcahy, J. P., Tang, Y., Yool, A., Wiltshire, A., et al. (2019). UKESM1: Description and evaluation of the UK Earth System Model. *Journal of Advances in Modeling Earth Systems*, *11*(12), 4513–4558. https://doi.org/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*(19), 7823–7843. https://doi.org/10.1175/JCLI-D-18-0134.1

Swart, N., Cole, J., Kharin, V., Lazare, M., Scinocca, J., Gillett, N., et al. (2019). The Canadian Earth System Model version 5 (CanESM5.0.3). *Geoscientific Model Development*, *12*(11), 4823–4873. https://doi.org/10.5194/gmd-12-4823-2019

Tatebe, H., Ogura, T., Nitta, T., Komuro, Y., Ogochi, K., Takemura, T., et al. (2019). Description and basic evaluation of simulated mean state, internal variability, and climate sensitivity of MIROC6. *Geoscientific Model Development*, *12*(7), 2727–2765. https://doi.org/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*(7), 4781–4796. https://doi.org/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. https://doi.org/10.1071/ES19035