



Can internal variability explain observed Antarctic sea ice expansion?

Robert R. Ford¹ and Brian E. J. Rose¹

¹Department of Atmospheric and Environmental Sciences, University at Albany, State University of New York, Albany, NY, USA

Correspondence: Robert R. Ford (rford2@albany.edu)

Abstract. Expansion of Antarctic sea ice was observed over the pre-2014 satellite record, and most climate models are not able to reliably simulate this expansion. Here, we explore the hypothesis that internal variability is enough to explain the expansion by analyzing two ensembles of the Community Earth System Model version 1.3, which have ocean/ice model resolutions of ~ 10 km (high-resolution; HR) and ~ 100 km (low-resolution; LR). The HR configuration often simulates Antarctic sea ice area (SIA) expansion in September of similar magnitude to observations, while LR rarely does. However, the zonal structure of the SIA expansion in HR has important discrepancies with observations, overemphasizing sea ice increases within the Weddell Sea ice pack. In the rare cases when LR has multidecadal SIA expansion similar to observations, it appears to get the zonal structure correct. Recovery from open-ocean deep convection explains the relative frequency of SIA expansion in HR, while the SIA expansion in LR is associated with variability in the Amundsen Sea low and the Pacific–South American pattern. We show that high-resolution modeling has the potential to help reconcile simulated Antarctic sea ice trends with observations, but the spatial patterns of the trends must be taken into consideration when assessing model performance.

1 Introduction

Satellite observations have shown that Antarctic sea ice increased from the beginning of the record in the late 1970s to about 2014, after which an ongoing rapid decline has been observed. The latest generation of climate models does not reliably capture this pre-2014 expansion, instead generally showing decreases in sea ice (Roach et al., 2020; Shu et al., 2020). Some CMIP-class models are capable of simulating Antarctic sea ice expansion under CO₂ forcing (Singh et al., 2019; Liu, 2025), but rarely does the spatial pattern of the expansion resemble observations (Roach and Polvani, 2026).

There are two questions of interest to understanding this subject, which are related but could plausibly have different answers: (1) why did Antarctic sea ice increase in observations up to 2014, and (2) why are models generally unable to simulate this increase? Part of what makes this problem so difficult is that the answers to these two questions could be different combinations of various mechanisms, but a quantitative attribution using climate models would require that we have confidence in the models' abilities to simulate those mechanisms. For the first question, the sea ice expansion may be entirely explainable as internal variability, or there may be a significant forced component. For the second question, there may be deficiencies in modeled internal variability, deficiencies in the forced response, or both.



25 There are two popular hypotheses on the forced response side, and typically, they are taken as an answer to both questions. First, anthropogenic stratospheric ozone depletion has strengthened the Southern Hemisphere westerlies, forcing a cooling response over the Southern Ocean (e.g., Purich et al., 2016a; Hartmann, 2022; Roach et al., 2023; Li et al., 2026; Wang et al., 2026). To explain the model–observation discrepancy, this process would have to be simulated too weakly by CMIP-class models, or perhaps the models are too sensitive to the other forcings that end up masking this cooling. Second, anthropogenically-
30 forced increases in meltwater from the Antarctic Ice Sheet have increased the stratification of the Southern Ocean, inhibiting the upward mixing of warmer subsurface waters and resulting in a cooler surface Southern Ocean (e.g., Bintanja et al., 2013; Rye et al., 2020; Dong et al., 2022; Schmidt et al., 2023). This would be an elegant solution to the discrepancy, since CMIP-class models generally lack active ice sheets (see, e.g., the SOFIA initiative, Swart et al., 2023).

For the ozone depletion hypothesis, there are a few issues. While most models show a Southern Ocean cooling response to
35 ozone depletion on interannual timescales, they show a warming response on multidecadal timescales (Ferreira et al., 2015; Holland et al., 2017). Polvani et al. (2021) showed that Southern Annular Mode (SAM) variability only explains about 15% of Antarctic sea ice variability on interannual timescales, making the relationship questionable to extrapolate to multidecadal timescales, regardless of sign. Similarly, Simpkins et al. (2012) and Dong et al. (2023) demonstrated that the observed SAM trend is not associated with a strong enough sea ice or Southern Ocean SST trend to explain observations. On top of this,
40 CMIP-class models generally capture the observed SAM trend (Holland et al., 2017; Bracegirdle et al., 2020; Dong et al., 2023), so the issue in models would need to be related to the ocean’s response to SAM, not the atmosphere’s response to ozone depletion.

For the Antarctic meltwater hypothesis, various studies (referenced above) have demonstrated that an idealized freshwater forcing of the Southern Ocean will cool its surface, but it appears that realistic amounts of freshwater are not enough to simulate
45 an observation-like expansion of the sea ice (Swart and Fyfe, 2013; Pauling et al., 2016). In addition, Zhu et al. (2026) have shown that a realistic meltwater forcing has a more complicated sea ice response, with increases and decreases in different sectors.

On the internal variability side, the variability of interest could be remotely forced by the tropical Pacific, local to the Southern Ocean, or related to the strength of the teleconnections between the two regions. Decadal-scale Pacific variability,
50 quantified by the interdecadal Pacific oscillation (IPO), has been linked to sea ice variability in the Pacific sector, with a cooler eastern Pacific (i.e., negative IPO) associated with increased sea ice in the Ross Sea (Meehl et al., 2016; Purich et al., 2016b; Chung et al., 2022) and decreased sea ice in the Bellingshausen Sea (Purich et al., 2016b), also associated with a deepening of the Amundsen Sea low (ASL). Like variability in the ASL, the Pacific–South American (PSA) pattern is another possible source of Pacific-sector sea ice anomalies (Schneider et al., 2012; Irving and Simmonds, 2016; Kohyama and Hartmann, 2016).

55 There is some evidence that eddy-parametrizing ocean models underestimate the magnitude of multidecadal variability that the oceans help generate (Jüling et al., 2021). Underestimated multidecadal variability could be the convective type that is found in some climate models (including the simulations studied here), or it could be stochastic variability associated with the explicit simulation of mesoscale eddies in the ocean, as suggested by Latif and Keenlyside (2011) and Jüling et al. (2020). As a result, standard-resolution modeling may not be sufficient for generating a realistic sample of Southern Ocean variability.



60 Recently, Bushuk et al. (2026) showed that the relationship between model resolution and variability in Antarctic sea ice trends is unclear, so more work is needed to understand how model resolution affects internal variability at multidecadal timescales.

When climate models are used to examine the role of internal variability in Antarctic sea ice trends, it is sometimes assumed that the modeled variability is generally correct (e.g., Chemke and Polvani, 2020), such that the model–observation discrepancy can be attributed to an error in the forced response. However, there is substantial uncertainty in the relative importance of
65 internal variability and externally-forced change for observed Antarctic sea ice trends over multidecadal timescales. In the absence of a long, reliable observational record of the Southern Ocean, this kind of decomposition into forced and unforced components would typically be done with climate models ensembles, but we know that models have systematic deficiencies over the region (Wills et al., 2022), hence the uncertainty surrounding this problem.

The hypothesis directly addressed in this study is that internal variability can explain the pre-2014 expansion, but it may also
70 help explain part of the post-2014 retreat. There is some evidence for this involving the 2016–2017 Maud Rise polynyas—after the polynyas, the Southern Ocean transitioned into a state with a saltier surface layer (Silvano et al., 2025). This could mean that we are now in a decadal-scale period of sea ice loss and greater mixing between the surface and subsurface Southern Ocean, after which there could be a return to slow sea ice expansion. To be clear, this hypothesis does not imply that anthropogenic forcing is unimportant over the Antarctic region. We would expect, as models have projected, that there is a slow decline in
75 Antarctic sea ice due to anthropogenic forcing, but on top of this decline, there may be internal variability of similar magnitude to the forced response, which many models are not able to simulate. With some recent work challenging the ozone depletion hypothesis (Polvani et al., 2021; Dong et al., 2023) and uncertainty around models’ responses to realistic meltwater forcing (Swart and Fyfe, 2013; Pauling et al., 2016; Zhu et al., 2026), we argue that the role of internal variability is worth investigating in more detail.

80 In two climate model ensembles with different horizontal resolutions, we test whether internal variability can help explain the recent phase of Antarctic sea ice expansion. In Sect. 2, we describe the model and observational data and outline the statistical methods we employ. In Sects. 3–5, we present our results and seek to answer the following question: how often do these models produce multidecadal periods of Antarctic sea ice expansion, and when they do, how realistic are the corresponding spatial patterns? In Sect. 6, we discuss mechanisms and implications, and we summarize and conclude in Sect. 7.

85 2 Data and methods

2.1 Models

We analyze output from runs of the Community Earth System Model version 1.3 (CESM1.3 Meehl et al., 2019; Chang et al., 2020) that were completed as part of the MESACLIP project (<https://project.cgd.ucar.edu/projects/MESACLIP/>). There are two ensembles of the CESM1.3 run with different component resolutions. More details on the differences are provided by
90 Meehl et al. (2019) and Chang et al. (2020), but most relevant here are the ocean and sea ice components: the high-resolution (HR) configuration uses the Parallel Ocean Program version 2 (POP2) and Community Ice Code version 4 (CICE4) with a 0.1° (~ 10 km) horizontal grid, while the low-resolution (LR) configuration uses the same components with a 1° (~ 100 km)



horizontal grid. The key difference between these configurations is that mesoscale ocean eddies are resolved in HR but must be parametrized in LR. There are 10 ensemble members for HR and 22 for LR. Both configurations are run with historical forcing
 95 from 1920–2005 and RCP 8.5 forcing from 2006–2100.

HR is known to have strong multidecadal variability in deep convection in the Weddell Sea (Chang et al., 2020; Diao et al., 2022; Ford and Rose, 2026), which we expected would dominate the Antarctic sea ice trends on the multidecadal timescales we are considering. It is worth briefly discussing the realism of such a model. The observed open-ocean polynyas of 1974–1976 (Carsey, 1980) and 2016–2017 (Campbell et al., 2019) were smaller than the typical size of polynyas produced by this
 100 model, but HR is capable of occasionally simulating realistically-sized polynyas (see Fig. 1a from Diao et al., 2022). It is true that HR produces polynyas too often relative to observations, but the observational record over the Southern Ocean is too short to rule out this type of variability with any confidence. Further, HR seems to be in the class of models that produces open-ocean polynyas in the Weddell Sea for the correct reason: interactions with Maud Rise. In some other convecting models, large open-ocean polynyas also occur in the Ross Sea (Mohrmann et al., 2021; Lu et al., 2026), which is unsupported by
 105 observations.

With these limitations in mind, we argue that it is still worth exploring the sea ice trends that result from HR. LR lacks large open-ocean polynyas and the accompanying variability, yet we know large open-ocean polynyas are a feature of the real climate system. To that end, we may think of these two CESM1.3 ensembles as extremes with respect to their ability to simulate open-ocean polynyas, with reality likely being somewhere in between.

110 2.2 Observations

We use three observational sea ice concentration (SIC) products, derived from satellite-based passive microwave sensors:

1. NOAA/NSIDC SIC Climate Data Record (CDR) version 6 (dataset G02202, Meier et al., 2026), which we refer to as “NSIDC”
2. EUMETSAT Ocean and Sea Ice Satellite Application Facility (OSI SAF) SIC CDR, specifically datasets OSI-450-a1
 115 (EUMETSAT OSI SAF, 2025) and OSI-430-a (EUMETSAT OSI SAF, 2022), which we refer to together as “OSI SAF”
3. Hadley Centre Sea Ice and Sea Surface Temperature dataset version 1 (HadISST1, Rayner et al., 2003)

There is a discontinuity in HadISST1 between 2008 and 2009 due to a sensor change (Screen, 2011), which creates an artificially large trend. Since HadISST1 is similar in magnitude to the other two products (Fig. 1) and does not provide a useful estimate of any trends including 2008–2009, we do not use HadISST1 for any trend analysis, keeping it only for climatologies.

120 The common period covered by the products is 1979–2024, and we choose the 29-year period 1986–2014 as the sea ice expansion phase of interest. In choosing this period, 2014 is a sensible end year, since the rapid decline started in 2015. With no particular reason to insist on starting with 1979, we note that 1986 is the pre-2014 September sea ice area minimum in both datasets (Fig. 4), so starting with 1986 produces a local maximum in the trend. Compared to starting with 1979, it is therefore a stricter test of the hypothesis that internal variability can explain the trend.



125 2.3 Sea ice metrics

We primarily examine SIC and sea ice area (SIA), computed by multiplying grid cell areas by SIC (as a fraction), then summing over area. When considering the zonal structure of the sea ice trends, we also compute SIA as a function of longitude, which we call SIA_λ for brevity. For the model data, which are on a 1° rectilinear grid, this is done by summing the product of grid cell area and SIC over latitude, and for the observational data, which are on a polar stereographic grid, this is done by collecting
 130 the SIC into 1° longitude bins and computing SIA within each bin. We choose SIA over sea ice extent (SIE) to facilitate direct comparison with recent model–observation assessments (e.g., Roach et al., 2020; Holmes et al., 2024; Roach and Polvani, 2026).

2.4 Trend analysis

We can decompose a trend β into parts resulting from external forcing (F) and internal variability (V):

$$135 \quad \beta = \beta_F + \beta_V \quad (1)$$

Since we are interested in the trends associated with the internal variability of the models, we subtract out the trends in the ensemble mean—an approximation of the forced component—from each ensemble member:

$$\beta_{i,V} = \beta_i - \beta_{i,F} \approx \beta_i - \bar{\beta} \quad (2)$$

where β_i is the total trend for ensemble member i , $\beta_{i,V}$ is the part of the trend due to internal variability, $\beta_{i,F}$ is the part of the
 140 trend due to external forcing, and $\bar{\beta}$ is the total trend for the ensemble mean.

This removal of the forced component is done for all 29-year trends: SIA, SIA_λ , and SIC. All trends are computed using ordinary least squares, and the standard error (SE) of observational SIA trends are corrected by a factor involving the lag-1 autocorrelation following Santer et al. (2000). Power spectra are estimated using the multitaper (Prieto, 2022) and Welch’s methods. As will be described in more detail later, we assess model–observation agreement between SIA_λ trends by computing
 145 the Pearson correlation coefficient over longitude.

3 Climatologies

To provide context for the following sections, we first present the 1979–2024 SIA climatologies for the models and observations in Fig. 1. The markers show the time-mean (and ensemble-mean for the models) SIA, and the error bars show the minimum and maximum SIA over the same period (again, across all ensemble members for the models). LR is close to observations, with
 150 the exception of most of the melt season (NDJF), where the sea ice does not melt fast enough in LR. HR has overall lower SIA than LR and observations, and it has a substantially larger range in the winter, where decade-long periods of deep convection and open-ocean polynyas in the Weddell Sea bring the average SIA well below the observed range. The upper range of HR is reasonable, which occurs during years without polynyas, so including only non-polynya years would produce better agreement with observations (cf. Fig. 3 from Chang et al., 2020).

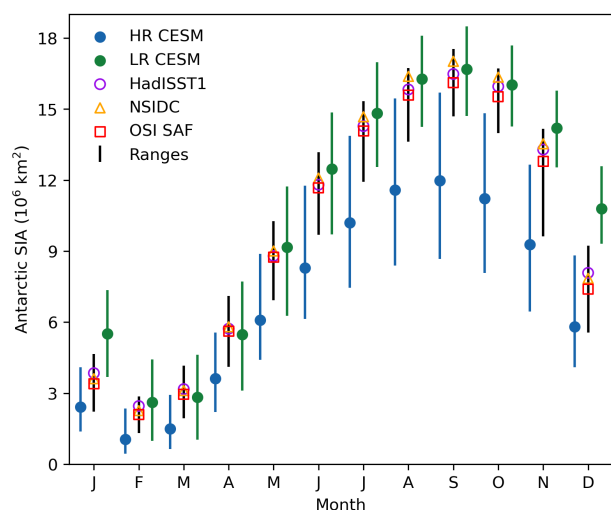


Figure 1. 1979–2024 climatologies of Antarctic sea ice area (SIA) across observational products and two versions of the CESM1.3.

155 We focus hereafter on September and February, the months of maximum and minimum sea ice in both observations and models. The choice to examine only individual months is essential here because annual- and seasonal-mean trends risk conflating trends happening over different months. For example, an annual-mean trend will show trends within the interior region of the annual-mean ice-covered area (e.g., see Fig. 1b from Liu, 2025). This could be interpreted as trends within the interior winter sea ice, but, in fact, the contribution comes from trends at the sea ice edge during the grow and melt seasons. This is particularly important for assessing a model like the HR CESM1.3, which does actually have trends in the sea ice interior during September.

165 In Figs. 2 and 3 we show the 1979–2024 average September and February SIC for the models and observations. The maps for the models are averaged over all ensemble members. For our purposes, there are no meaningful differences among the three observational products. In Fig. 2d, the impact of open-ocean polynyas is clear: the low SIC is centered around Maud Rise with a secondary SIC minimum to the west in the central Weddell Sea. Further, the mean sea ice edge is at a higher latitude over the other sectors. This is the result of an overall warmer Southern Ocean, as the deep convection brings warmer waters to the surface, which are then advected around the rest of the Southern Ocean. LR, in Fig. 2e, more closely resembles observations. For the February maps in Fig. 3, there is barely any sea ice in HR, and LR overestimates the amount of sea ice in the Weddell Sea away from the Antarctic Peninsula.

170 4 Variability and trends

With the context from the climatologies, we show in Fig. 4 the timeseries of SIA for the models and observations. The solid blue and green lines show the ensemble-mean SIA for HR and LR, and the shading around those lines show the ensemble

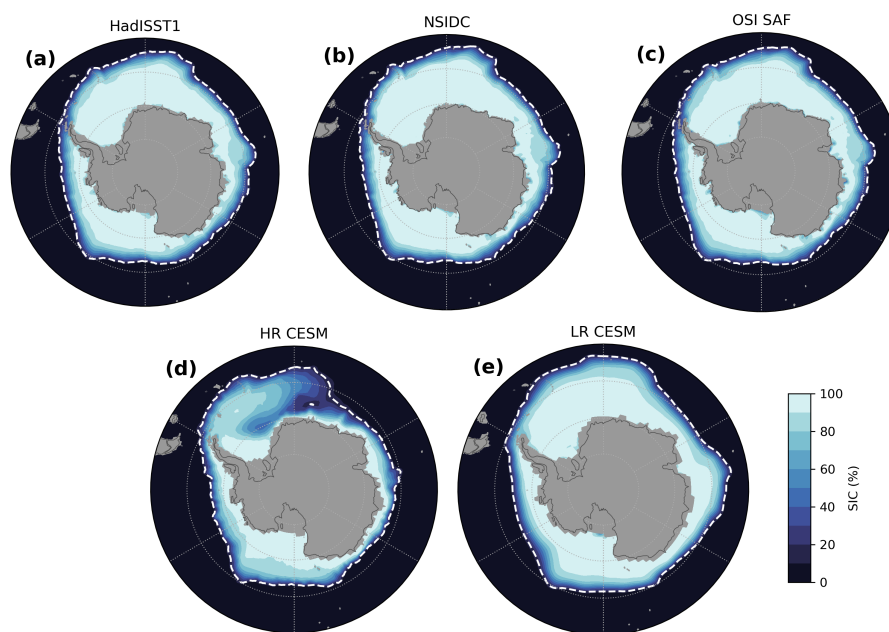


Figure 2. Maps of September sea ice concentration (SIC) averaged over 1979–2024 across (a–c) observational products and (d, e) two versions of the CESM1.3.

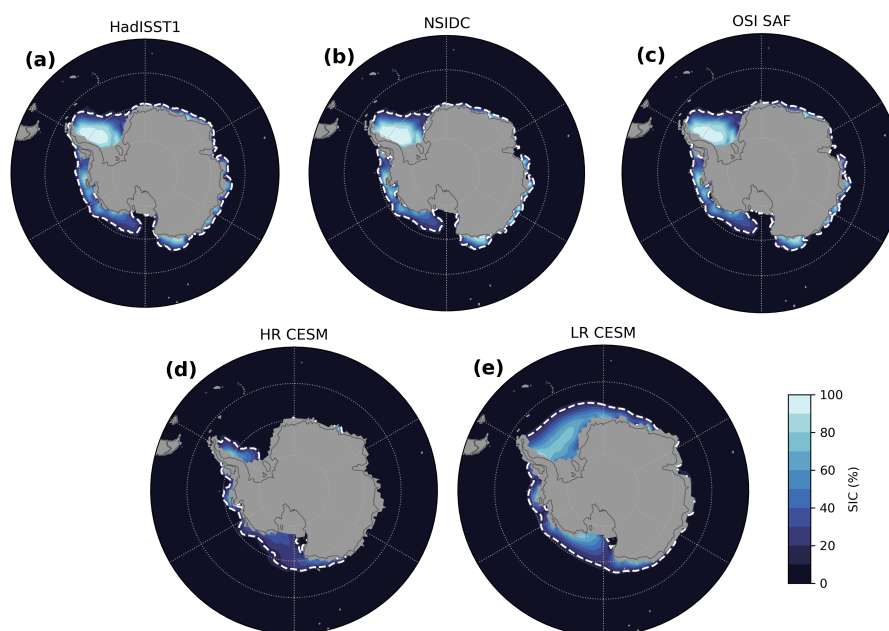


Figure 3. As in Fig. 2, but for February.

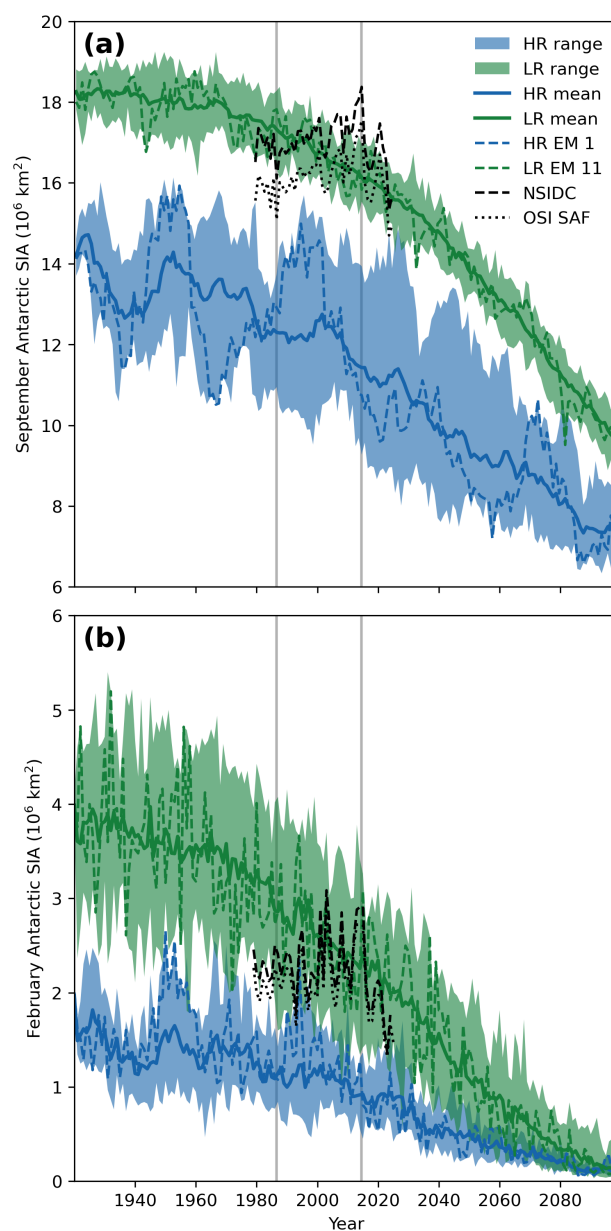


Figure 4. Time series of (a) September and (b) February Antarctic sea ice area (SIA) in HR and LR CESM1.3 (1920–2100; historical and RCP8.5 forcing) and two observational products (1979–2024) described in the text. The CESM1.3 ensemble means are plotted in the solid lines, while the ensemble ranges are plotted in the blue and green envelopes. One ensemble member each is plotted for HR and LR in the blue and green dashed lines, corresponding to the ensemble members plotted in Fig. 9e,f. For reference, the two gray vertical lines indicate the period used to compute the observed trends (1986–2014).

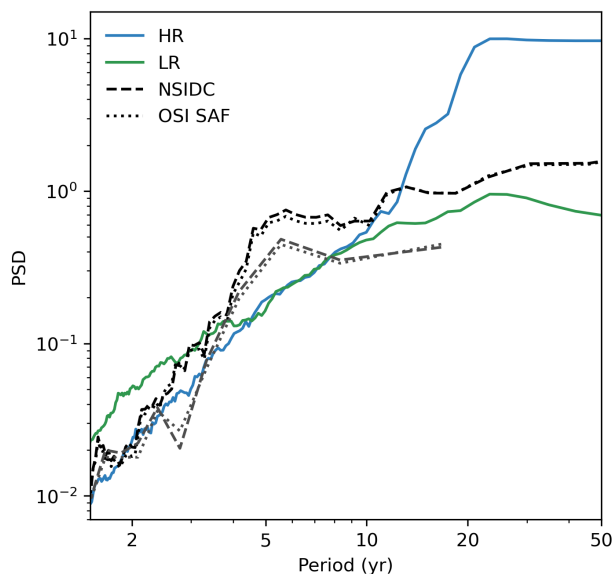


Figure 5. Spectral density estimates of 12-month running mean Antarctic sea ice area (SIA) in HR and LR CESM1.3 (1920–2024) and two observational products (1978–2025). The CESM1.3 power spectra are estimated for each ensemble member, then averaged; they are estimated with the multitaper method, while the observational power spectra are estimated with both the multitaper (black) and Welch’s (gray) methods to check robustness.

range. From this we can see how the larger range of variability in the September SIA of HR evolves over time. Starting from nearly the same initial conditions, the HR ensemble follows the same phase of multidecadal variability for about 30 years (i.e., 1920–1950). Then after around 1950, the ensemble diverges into different phases and the ensemble-mean is mostly decreasing. LR has a greater range of variability than HR in February, certainly due to HR having so little February sea ice in the first place (Fig. 3d).

One ensemble member each of HR and LR is indicated by the dashed lines in Fig. 4. Focusing on September, we can see times when both configurations are capable of producing at least decade-long periods of Antarctic sea ice expansion. This possibility has been noted before in a variety of models (e.g., Singh et al., 2019; Liu, 2025), but here we want to explore further how realistic these expansion periods are. For HR, as we will discuss later, these periods of expansion can be interpreted as a recovery from relatively low sea ice associated with a period of Weddell Sea deep convection (Ford and Rose, 2026).

One way to assess the skill of these two CESM1.3 configurations is to examine the power spectra of the SIA time series. Figure 5 shows the power spectral density for detrended Antarctic SIA in HR, LR, and observations, estimated using the multitaper method (plus an additional estimation using Welch’s method for observations). We use 12-month running mean SIA for the spectral estimates in order to avoid the aliasing that would result from using individual months (Madden and Jones, 2001). Using anomalies would result in a spectral peak centered at 1 year due to multidecadal changes in the seasonality of the



anomalies. An idealized sketch of what happens when anomalies are used for this type of time series is shown by Möller et al. (2008) (their Fig. 8b).

190 Already from Fig. 4, it can be inferred that HR has greater power at multidecadal periods, and this is reflected in the spectra. It also shows that HR has lower power over the 2–5 year range. This appears to agree with Jüling et al. (2021), who found a similar spectral shift in a different pair of high- and low-resolution CESM simulations for other variables, including sea surface temperature and ocean heat content. Both configurations lack the spectral peak at 5–6 years which is present in the observations. This 5–6-year variability can be seen clearly in the observational time series (Fig. 4) as the most prominent
 195 timescale of variability outside of the long-term trends. It is important to note that, while LR appears to agree better with observations on the multidecadal side of the spectrum, the spectral density estimates for observations have a large amount of uncertainty in that range, since the analyzed time series is only about 47 years long. It is shown for the sake of completeness, but we cannot infer from it that LR has more observation-like multidecadal variability.

We now address the question posed in the introduction: if the kind of variability exhibited by the HR and LR CESM1.3
 200 existed in nature, how often would we expect to see a multidecadal increase in Antarctic sea ice similar to that observed due to internal variability alone? To quantify this, we begin by computing all consecutive and overlapping 29-year trends in the models' Antarctic SIA over the period 1950–2014 for HR and 1930–2014 for LR for both September and February. Then, we remove the corresponding ensemble-mean SIA trend for each 29-year window as an estimate of the forced response, leaving us with an estimate of the SIA trend due to internal variability (Eq. 2). We exclude the first 30 years of HR because the
 205 internal variability of the ensemble appears to be in phase and therefore the ensemble mean is a poor approximation of the forced component of the trend. The first 10 years of LR are excluded for the same reason, though the internal variability of the ensemble is not visibly in phase.

We choose a wider range than the observed trend (1986–2014) because we are assessing the role of internal variability—there is no reason to expect that variability in a free-running climate model is in phase with observations. Comparing models
 210 and observations only over the same time window (1986–2014 here or more commonly in other studies ~1979–2014) will result in undersampled spatial patterns of a model's internal variability. For these CESM1.3 ensembles, we would only have one sample each for September in LR and February in HR, two samples for February in LR, but zero for September in HR (the open circles in Fig. 6). This is clearly not enough to do any statistical analysis of the spatial patterns of the trends. Using our approach of considering all consecutive and overlapping trends, there are 370 HR trends and 1254 LR trends, many more than
 215 typically analyzed when comparing only the same time window in large ensembles and CMIP ensembles. Histograms of these trends for September and February are shown in Figure 6. In addition, we plot the observed trends over 1986–2014 for both NSIDC and OSI SAF with the SE of these trends as a measure of uncertainty.

Consider the September trends in Fig. 6a. Under the variability of HR, the observed trend would be completely ordinary because of its greater variance and more uniform distribution. Despite only 8% of samples agreeing with observations, if we
 220 reframe the question as asking what percent of the HR trends are at least as positive as the observed SE, then we would get 38%. Under the variability of LR, which has lower variance, the observed trend would be unusual but plausible (1.6–2.7 standard

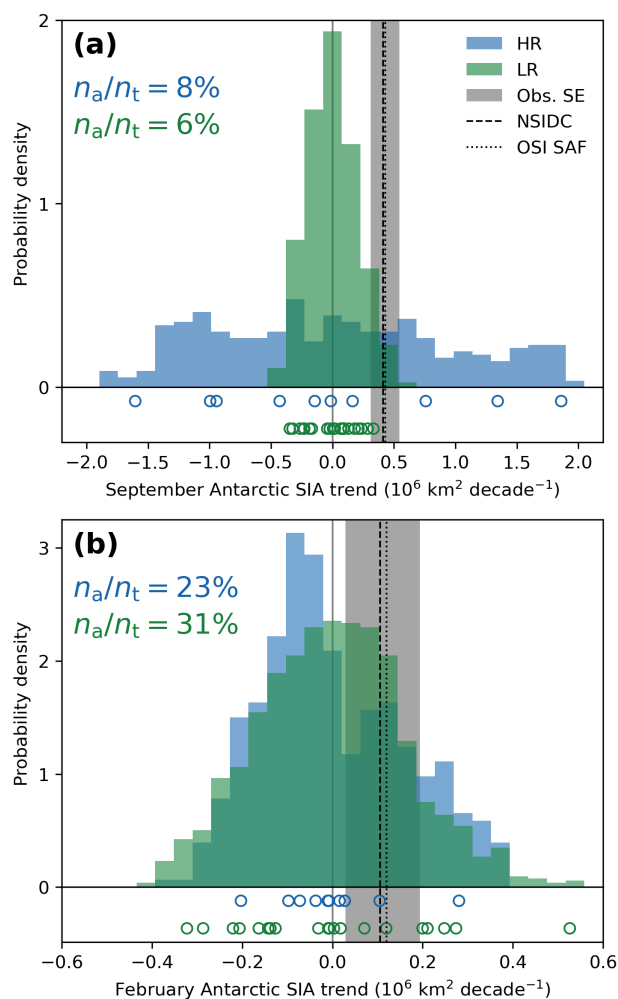


Figure 6. Histograms of all overlapping 29-year (a) September and (b) February Antarctic sea ice area (SIA) trends in HR and LR CESM1.3 within 1950–2014 (HR) or 1930–2014 (LR) associated with internal variability. The 1986–2014 observed trends are plotted as the dashed and dotted black lines. The observational standard error (SE) is taken as the largest range between the two observational products’ SEs. In both panels, the fractions of total samples (n_t) that agree with observations (i.e., are within the observational SE; n_a) are shown for both HR and LR as percentages. Below the histograms, the blue (HR) and green (LR) open circles show the modeled 1986–2014 trends associated with internal variability.

deviations above the mean for the observed SE). For both model configurations, the February trends have similar distributions, and because the trends tend to be smaller than in September, many more samples fall within the observational uncertainty.

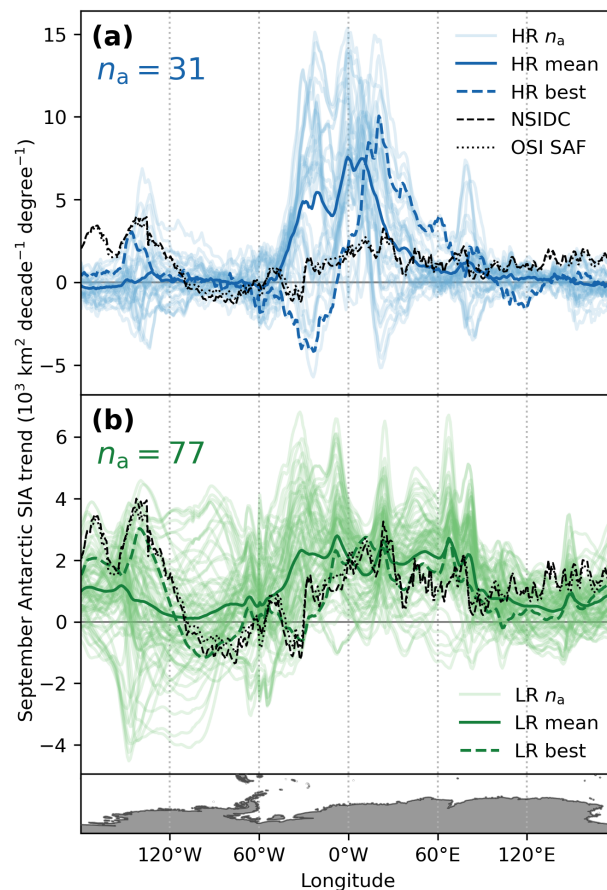


Figure 7. September sea ice area (SIA) trends as a function of longitude for (a) HR and (b) LR that are within the observed SIA trend standard error shown in Fig. 6. Note the different vertical axis scale between the panels. The number of modeled trends (samples) plotted in each panel is indicated by n_a . The darker blue/green solid lines indicate the average of the n samples, while the darker blue/green dashed lines indicate the sample with the highest (“best”) correlation with observations over longitude.

5 Spatial patterns

225 In this section, we view sea ice trends in two ways: as a function of longitude (SIA λ) and as SIC maps. The observed September and February SIA λ trends are shown in the black dashed and dotted lines in Figs. 7 and 8. The main features in September are expansion in the Ross and western Weddell Seas, and retreat in the Bellingshausen and eastern Weddell Seas. In February, trends are more geographically limited by the strong seasonality of Antarctic sea ice, but the main pattern is expansion off the east coast of the Antarctic Peninsula and a dipole around the Ross Sea. These trends are also shown as maps in Figs. 9 and 10.

230 For each sample within the observed SEs (see Fig. 6), the corresponding SIA λ trend is plotted in Figs. 7 and 8, and the mean of

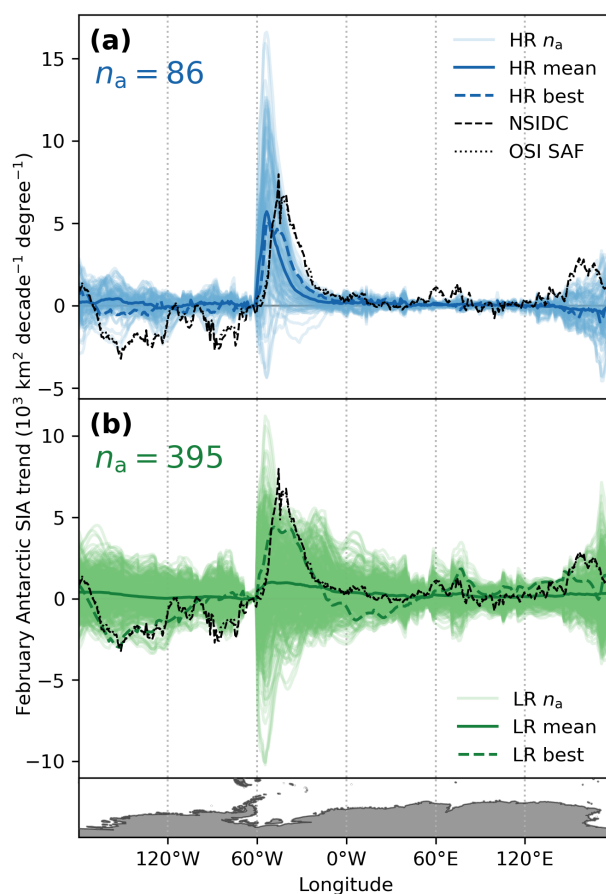


Figure 8. As in Fig. 7, but for February.

all of the samples is plotted in the darker solid lines. The question the mean addresses is: on average, what is the model doing when it appears to agree with observations in the hemisphere-wide trend?

Starting with Fig. 7a, which shows HR trends in September, we can see that most of the samples show large increases in the Weddell Sea, while the trends elsewhere cover a mostly symmetric range of positive to negative. As Roach and Polvani (2026) recently discussed, models in the CMIP6 ensemble that are able to simulate increases in SIA of the same magnitude as observations show unrealistic spatial patterns, often large regions within the ice pack of the Weddell and Ross Gyres. The conclusion is similar here, with some important differences. It is true that HR overemphasizes the sea ice interior (Fig. 9c), but it seems better than some other convecting models (compare Fig. 5 from Roach and Polvani, 2026), since it also shows significant increases along the sea ice edge, similar to observations.

Now for LR in September, Fig. 7b shows overall lower and more realistic SIA trends. Most of the samples show an increase in the eastern Weddell Sea and Ross Sea, though there is some spread in the pattern. The mean LR SIA trend appears to agree quite well with observations; it is just a bit weak in the Ross and Bellingshausen Seas. The zonally-constrained February trends

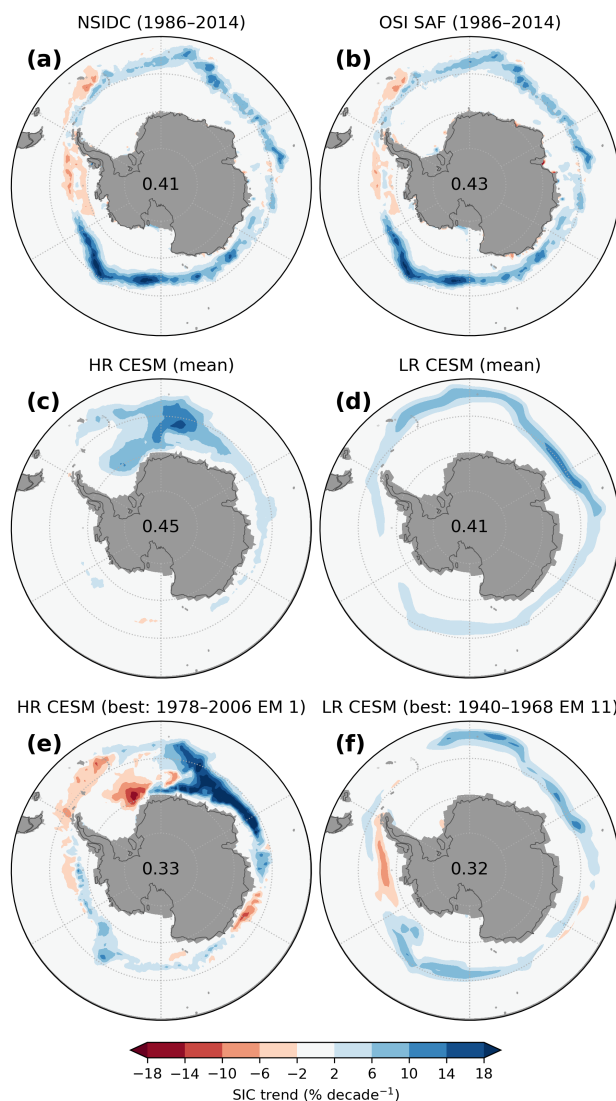


Figure 9. Maps of September sea ice concentration (SIC) trends. (a, b) Observed SIC trends over 1986–2014. (c) HR and (d) LR SIC trends averaged over all samples that agree with the observed sea ice area (SIA) trend (corresponding to Fig. 5 solid “mean” lines). (e) HR and (f) LR SIC trends that best match the observed SIA trends over longitude (corresponding to Fig. 5 dashed “best” lines), with the corresponding time spans and ensemble members are given in the panel titles. The number in the center of each map is the corresponding hemisphere-wide SIA trend in units $10^6 \text{ km}^2 \text{ decade}^{-1}$.

are partially captured by HR (Fig. 8a mean), mainly in the Weddell Sea. LR, on the other hand, tends to show evenly distributed increases and decrease in all sectors, so the mean trend is small almost everywhere.

245 In all of these mean SIA_λ trends, we are averaging over various types of internal variability. We now address a second question: are the models capable of simulating a sea ice trend that looks like observations, no matter how infrequently? The

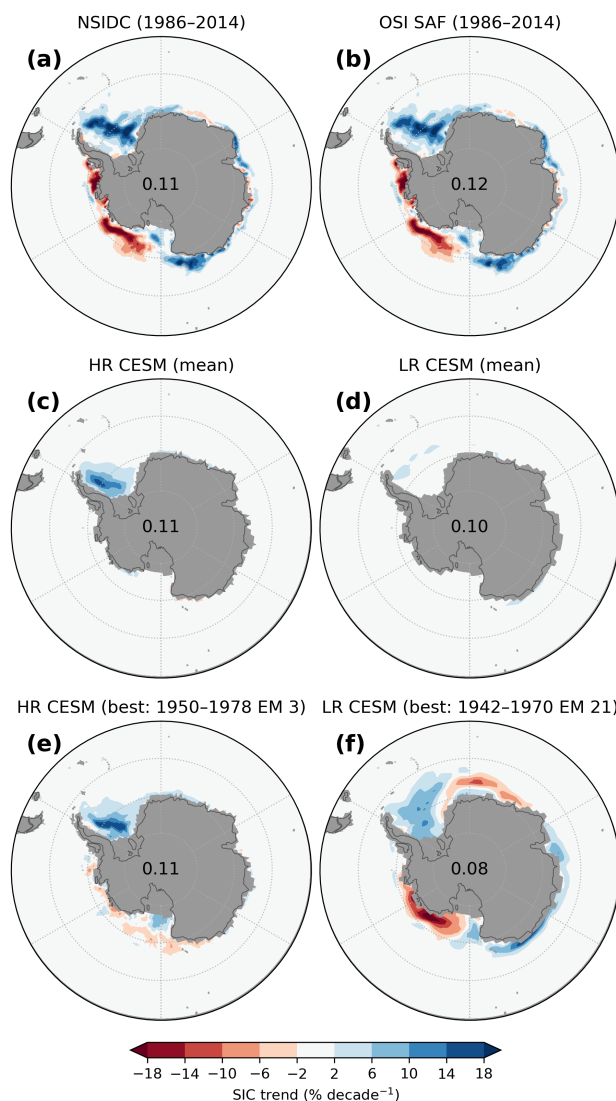


Figure 10. As in Fig. 9, but for February.

approach we take is to simply compute the correlation between each modeled SIA λ trend and the observed SIA λ trends, taking the sample with the highest correlation as the “best” SIA λ trend. There are other metrics that could assess the spatial patterns, but this approach has an important advantage. A pixel-by-pixel comparison of the models and observations—whether correlation, root mean square error, or something else—would not work well because small differences in the location of the sea ice edge would substantially reduce the skill metric, even if the simulated zonal structures were otherwise reasonable. We know that HR has overall lower sea ice (Fig. 2), so such a metric would always show low skill. Using the root mean square



error for SIA λ gave the same best-fit samples except for HR in September, where it selected a sample with a generally less realistic zonal pattern (not shown).

255 The trends resulting from this procedure (which are the same regardless of whether NSIDC or OSI SAF were used) are shown in Figs. 7 and 8 as the blue or green dashed lines, and the corresponding maps are presented in Figs. 9e,f and 10e,f. In September, both HR and LR are able to produce trends with qualitatively correct zonal structures: increases in the Weddell and Ross Seas and a decrease near the Antarctic Peninsula. Again, HR has SIC trends within the interior Weddell Sea that are not present in observations (Fig. 9e), and the Atlantic–Indian sector has much more rapid sea ice expansion than observed. The LR
 260 September map (Fig. 9f) looks quite similar to observations, though the Ross sector trend is too weak. In February, the best trends for HR and LR (Fig. 10e,f) both appear reasonable, but HR has better agreement in the Atlantic sector, while LR has better agreement in the Pacific sector.

6 Discussion

6.1 Convective variability in the high-resolution model

265 It has been proposed that internal variability associated with deep convection may be responsible for (or at least contributes to) the observed Antarctic SIA expansion, particularly as a phase of recovery from the Weddell Sea polynyas of the 1970s (Zhang et al., 2019). The coinciding of the 2016–2017 Maud Rise polynyas with the post-2014 SIA retreat keeps this hypothesis afloat (e.g., Morioka et al., 2024). There is also some evidence for a drop in Antarctic SIA in the 1970s (Goosse et al., 2024), which would be consistent with the hypothesis that the sea ice expansion period is a slow recovery from a period of open-ocean deep
 270 convection.

By comparing the mean and best maps in Fig. 9, we can begin to make some inferences about the nature of these trends. In the HR mean SIC trend (Fig. 9c), we see the importance of Weddell Sea deep convection for permitting the sea ice expansion. In the HR best SIC trend (Fig. 9e), we see that the location of sea ice expansion is shifted eastward, i.e., downstream. At the same time, there is sea ice loss in the central Weddell Sea. From this spatial pattern and the corresponding SIA time series
 275 (see the dashed blue line in Fig. 3), we can infer that this trend is the result of a period of recovery from Weddell Sea deep convection plus the beginning of a new phase of deep convection. It seems like this transition between the phases of variability allows for sea ice loss around the Antarctic Peninsula. We may also infer that, even if this type of convective variability is wholly responsible for the observed SIA expansion, it is still too strong in the model because the period of sea ice expansion alone would have fallen outside of the SE of the observed trend on the high end. Another interpretation is that the timescale
 280 of the convective variability may be too short in HR—a slower variability could result in a weaker trend that more closely resembles observations.

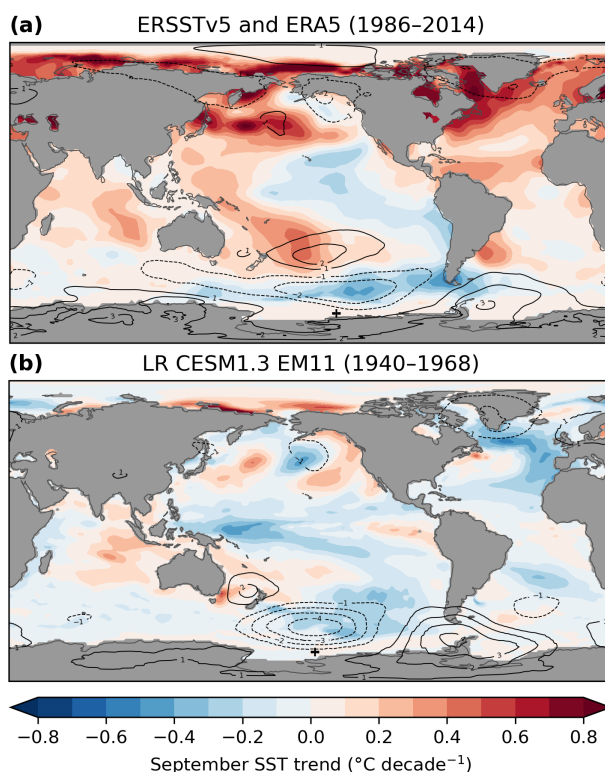


Figure 11. September sea surface temperature (SST; shading) and sea level pressure (SLP; black contours in $1 \text{ hPa decade}^{-1}$ intervals) trends in (a) observations over 1986–2014 and (b) the LR CESM1.3 corresponding to the period (1940–1968) and ensemble member (11) whose September sea ice trend pattern best matches observations (i.e., Fig. 9f). For observations, the NOAA Extended Reconstructed SST V5 (ERSSTv5; Huang et al., 2017) and ERA5 (Hersbach et al., 2020) SLP are used. The ensemble-mean trends are subtracted from the LR CESM1.3 trends to remove the forced component. The plus signs indicate the average September location of the Amundsen Sea low for the periods over which the trends are computed.

6.2 Non-convective variability in the low-resolution model

For LR, the story is completely different. Comparing the mean and best LR SIC trends (Fig. 9d,f), we see a similar pattern. The usual hypothesis is that the observed SIA increases are associated with local atmospheric variability (i.e., SAM, ASL, and the PSA pattern), Pacific variability (i.e., ENSO and IPO), or their combined impacts (Meehl et al., 2016; Purich et al., 2016b; Chung et al., 2022). The results of Purich et al. (2016b) show that a transition from positive to negative IPO in a different version of the CESM is associated with SIC increases in the Ross Sea and decreases in the Amundsen–Bellingshausen Sea—qualitatively similar to the pattern shown in Fig. 9f but with lower magnitudes.

In Figure 11, we show trends in September SST and sea level pressure (SLP) associated with the observed SIA expansion and the best-fit SIA expansion in LR. The SST trend in LR (Fig. 11b) does not suggest any notable shift in the IPO. In addition,



an IPO shift is likely not enough to explain the observed or modeled increases in the Atlantic–Indian sector. The SLP trend in Figure 11b instead resembles a PSA-like pattern associated with propagating atmospheric Rossby waves (Mo and Higgins, 1998). Equivalently, we may interpret the SLP trend as a deepening of the ASL, which is consistent with the observed and modeled decrease in eastern Pacific-sector sea ice loss (Turner et al., 2016). It is possible that similar atmospheric dynamics are responsible for the sea ice expansion in the Atlantic–Indian sector, since the positive SLP trend over the Antarctic Peninsula (Fig. 11b) is associated with anomalous southerly winds over the Weddell Sea. It may also be that stochastic variability (i.e., red noise associated with the thermal integration of weather) is a sufficient explanation for the sea ice expansion in the Atlantic–Indian sector.

A somewhat similar PSA-like pattern is seen in the observed SLP trend (Fig. 11a), but the centers of action are shifted to the east. This would be consistent with the fact that the negative sea ice trends also extend eastward into the western Weddell Sea in observations (Fig. 9a,b). It is important to note that the observed trends include the anthropogenically-forced response, which includes the ozone-driven trend in the SAM, so we cannot make a clean comparison here. Still, we may speculate from this that there are common processes responsible for some aspects of the sea ice expansion in LR and observations—namely, some combination of decadal Pacific variability and extratropical atmospheric variability, the complexities of which we leave for future study.

6.3 Prospects for reconciling models and observations

For the OSI SAF and NSIDC sea ice products, the recovery from the large 1974–1976 Weddell Sea polynyas is excluded, so unsurprisingly, we see no trend in September within the Weddell Sea. Without knowing with confidence how the sea ice evolved over the decades preceding the Weddell Sea polynyas, we can only speculate about how realistic the HR trends are. We venture that some of the Atlantic-sector expansion is associated with convective variability, but it is unlikely to be wholly responsible. In the context of Antarctic sea ice, the increase in resolution in the CESM1.3 is a double-edged sword—it allows for reconciling SIA/SIE trends with observations at the expense of a worse climatology and overreliance on Weddell Sea deep convection to produce those trends. Perhaps one way to improve model performance in this case is to figure out how to tune the model such that *some* intermittent deep convection is permitted, just not as much as the HR CESM1.3 and similar models produce. There is still the possibility that high-resolution modeling can help reconcile the observed and modeled sea ice trends without relying on oscillations in deep convection, but, at the moment, that work would need to be carried out with a different set of models.

LR, which is a typical CMIP-class model, is capable of simulating the particular Antarctic sea ice trend pattern seen in observations. Even if we consider the forced response of Antarctic sea ice to be approximately zero (i.e., by removing the ensemble mean as the forced component), the magnitude of the observed expansion is still quite rare in LR. Reconciliation between models and observations could come from a greater magnitude of internal variability, or it could come from a strongly negative local feedback process (e.g., cooling from meltwater).



7 Summary and conclusions

In this work, we quantified a large set of Antarctic sea ice trends across two CESM1.3 ensembles with different horizontal
 325 grid spacing and compared them to observations. We showed that it is not enough to only compare SIA/SIE time series. The
 frequent sea ice expansion in HR is due to variability in Weddell Sea deep convection, while the comparatively rarer sea
 ice expansion in LR is associated with internal atmospheric variability—in particular, a PSA-like mode. The CMIP6 models
 analyzed by Roach and Polvani (2026) that exhibit observation-like SIA expansion mostly align with the results of HR here,
 but it would be useful to know if there are more models in the CMIP ensemble that behave more like LR.

330 In order to improve models, we need more detailed assessment of Antarctic climate trends, at least taking into consideration
 zonal structure. When assessing the role of internal variability in observed trends, we recommend taking advantage of the entire
 simulation, not just the same modeled period as the observed trend. The exception is if a sufficiently large ensemble is used
 that can capture a representative sample of the spatial patterns of internal variability, which is not the same as an ensemble
 capturing a representative sample of global- or hemisphere-wide trends.

335 Ultimately, the challenge with the internal variability hypothesis is that we do not have confidence that models are able to
 sufficiently simulate the multidecadal variability of the Southern Ocean, which stems from the uncertainty in the observed
 variability of the Southern Ocean. Both ensembles examined here capture some aspects of the observed pre-2014 sea ice
 expansion, but neither ensemble satisfyingly captures all aspects. We are left to conclude that internal variability, as simulated
 by LR, is able to explain the observed Antarctic sea ice expansion if we are willing to accept that we just happen to be on
 340 an unusual path of internal variability. Alternatively, variability in Weddell Sea deep convection may play a non-negligible
 role in the Atlantic sector, leaving room for other modes of variability (e.g., IPO, SAM, and the PSA pattern) to explain the
 Pacific-sector sea ice trends.

Appendix A: Apparent ensemble member synchronization

We show in Fig. A1 a curious aspect of the HR ensemble. The Antarctic SIA for all ensemble members is shown, with two
 345 pairs highlighted in purple and orange. Each pair has multidecadal variability largely in the same phase, while the two pairs are
 roughly antiphased. This ensemble was produced by branching off from an initial simulation and applying small atmospheric
 perturbations (Chang et al., 2025), which is done to generate a range of internal variability. The convective variability of the
 Southern Ocean in this ensemble is mostly in phase at first, with a decadal decrease in SIA, followed by a spread in the rate of
 SIA recovery (i.e., the purple lines are quicker to recover to a non-convecting state, while the orange lines take longer).

350 We speculate that this rate of SIA recovery sets up these pairs for their later phase of variability, but that does not explain
 why they appear to become better aligned over time. Assuming there are no reasons outside the model for this apparent
 synchronization, it could be a coincidence, but 4 out of 10 ensemble members exhibiting this behavior seems unlikely. If it is
 neither a mistake nor coincidence, it could have implications for decadal predictability in this model—knowing the phase of
 variability near the start of the simulation has some skill in predicting the phase many decades later. This unusual aspect of the
 355 HR ensemble was also mentioned recently by Bushuk et al. (2026), but for now, it remains unexplored.

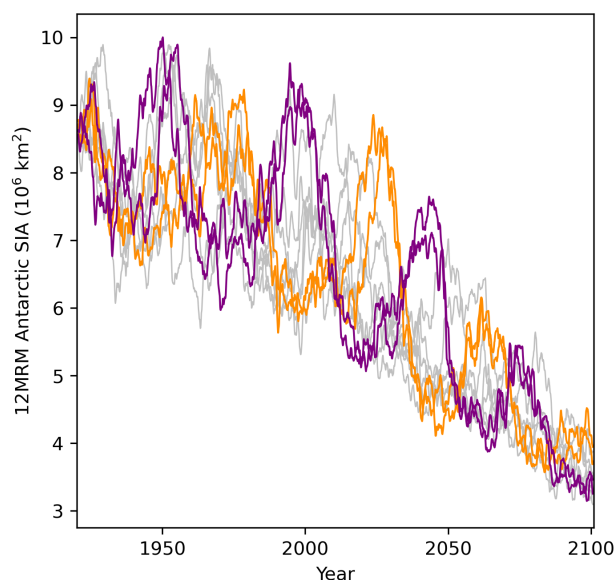


Figure A1. 12-month running mean Antarctic sea ice area (SIA) for all HR ensembles members. The two pairs of ensemble members that appear to be synchronized are shown in purple and orange.

Code and data availability. Jupyter Notebooks reproducing all analysis and figures are archived on Zenodo via GitHub (Ford, 2026). The CESM1.3 data were initially accessed through the NCAR Geoscience Data Exchange (Castruccio et al., 2024a, b, 2025). Regrided versions of the CESM1.3 SIC and SST data were downloaded via a Globus Guest Collection, which was accessed at <https://usclivar.org/meetings/high-resolution-modeling-data-access>. The NSIDC dataset (Meier et al., 2026) was downloaded from <https://nsidc.org/data/g02202/versions/6>. The OSI SAF (EUMETSAT OSI SAF, 2022, 2025) and ERA5 datasets were downloaded from the Copernicus Climate Change Service Climate Data Store (<https://cds.climate.copernicus.eu/datasets>). The HadISST1 SIC dataset (Rayner et al., 2003) was downloaded from <https://www.metoffice.gov.uk/hadobs/hadisst/data/download.html>. NOAA ERSSTv5 is provided by the NOAA PSL and was downloaded from their website at <https://psl.noaa.gov/data/gridded/data.noaa.ersst.v5.html>.

Author contributions. RF and BR conceptualized the study. RF performed the analysis and wrote the initial draft. Both authors interpreted the results and edited the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

<https://doi.org/10.5194/egusphere-2026-6178>

Preprint. Discussion started: 16 October 2026

© Author(s) 2026. CC BY 4.0 License.



Acknowledgements. We thanks the iHESP and MESACLIP teams for producing and archiving the CESM1.3 simulations. This work was supported by National Science Foundation (NSF) Award 2324302 and a computing allocation on the Derecho system (CISL, 2023), provided by the NSF National Center for Atmospheric Research.



370 References

- Bintanja, R., van Oldenborgh, G. J., Drijfhout, S. S., Wouters, B., and Katsman, C. A.: Important role for ocean warming and increased ice-shelf melt in Antarctic sea-ice expansion, *Nature Geoscience*, 6, 376–379, <https://doi.org/10.1038/ngeo1767>, 2013.
- Bracegirdle, T. J., Holmes, C. R., Hosking, J. S., Marshall, G. J., Osman, M., Patterson, M., and Rackow, T.: Improvements in Circumpolar Southern Hemisphere Extratropical Atmospheric Circulation in CMIP6 Compared to CMIP5, *Earth and Space Science*, 7, e2019EA001065, <https://doi.org/10.1029/2019EA001065>, 2020.
- Bushuk, M., Bonan, D. B., Griffies, S. M., Gregory, W., Zhang, Y., Hurlin, B., Chen, Y.-T., Rackow, T., and Goessling, H. F.: Historical and Projected Antarctic Sea Ice Trends Across High-Resolution Coupled Model Hierarchies, *Geophysical Research Letters*, 53, e2026GL124043, <https://doi.org/10.1029/2026GL124043>, 2026.
- Campbell, E. C., Wilson, E. A., Moore, G. W. K., Riser, S. C., Brayton, C. E., Mazloff, M. R., and Talley, L. D.: Antarctic offshore polynyas linked to Southern Hemisphere climate anomalies, *Nature*, 570, 319–325, <https://doi.org/10.1038/s41586-019-1294-0>, 2019.
- Carsey, F. D.: Microwave Observation of the Weddell Polynya, *Monthly Weather Review*, 108, 2032–2044, [https://doi.org/10.1175/1520-0493\(1980\)108<2032:MOOTWP>2.0.CO;2](https://doi.org/10.1175/1520-0493(1980)108<2032:MOOTWP>2.0.CO;2), 1980.
- Castruccio, F., Chang, P., Danabasoglu, G., Fu, D., Rosenbloom, N., Zhang, Q., King, T., and Liu, X.: MESACLIP: Nominal 1-degree CESM (low-resolution) simulations corresponding to high-resolution experiments, <https://doi.org/10.5065/DBZQ-1K04>, artwork Size: 124.655 Tbytes Pages: 124.655 Tbytes, 2025.
- Castruccio, F. S., Chang, P., Danabasoglu, G., Fu, D., Rosenbloom, N. A., Zhang, Q., King, T., and Liu, X.: MESACLIP: A 10-member ensemble of CESM HR historical (1920-2005) simulations, <https://doi.org/10.5065/7N1X-K278>, 2024a.
- Castruccio, F. S., Chang, P., Danabasoglu, G., Fu, D., Rosenbloom, N. A., Zhang, Q., King, T., and Liu, X.: MESACLIP: A 10-member ensemble of CESM HR RCP 8.5 (2006-2100) simulations, <https://doi.org/10.5065/PNCR-5S34>, 2024b.
- Chang, P., Zhang, S., Danabasoglu, G., Yeager, S. G., Fu, H., Wang, H., Castruccio, F. S., Chen, Y., Edwards, J., Fu, D., Jia, Y., Laurindo, L. C., Liu, X., Rosenbloom, N., Small, R. J., Xu, G., Zeng, Y., Zhang, Q., Bacmeister, J., Bailey, D. A., Duan, X., DuVivier, A. K., Li, D., Li, Y., Neale, R., Stössel, A., Wang, L., Zhuang, Y., Baker, A., Bates, S., Dennis, J., Diao, X., Gan, B., Gopal, A., Jia, D., Jing, Z., Ma, X., Saravanan, R., Strand, W. G., Tao, J., Yang, H., Wang, X., Wei, Z., and Wu, L.: An Unprecedented Set of High-Resolution Earth System Simulations for Understanding Multiscale Interactions in Climate Variability and Change, *Journal of Advances in Modeling Earth Systems*, 12, e2020MS002298, <https://doi.org/10.1029/2020MS002298>, 2020.
- Chang, P., Fu, D., Liu, X., Castruccio, F. S., Prein, A. F., Danabasoglu, G., Wang, X., Bacmeister, J., Zhang, Q., Rosenbloom, N., King, T., and Bates, S. C.: Future extreme precipitation amplified by intensified mesoscale moisture convergence, *Nature Geoscience*, pp. 1–9, <https://doi.org/10.1038/s41561-025-01859-1>, 2025.
- Chemke, R. and Polvani, L. M.: Using Multiple Large Ensembles to Elucidate the Discrepancy Between the 1979–2019 Modeled and Observed Antarctic Sea Ice Trends, *Geophysical Research Letters*, 47, e2020GL088339, <https://doi.org/10.1029/2020GL088339>, 2020.
- Chung, E.-S., Kim, S.-J., Timmermann, A., Ha, K.-J., Lee, S.-K., Stuecker, M. F., Rodgers, K. B., Lee, S.-S., and Huang, L.: Antarctic sea-ice expansion and Southern Ocean cooling linked to tropical variability, *Nature Climate Change*, 12, 461–468, <https://doi.org/10.1038/s41558-022-01339-z>, 2022.
- CISL: Derecho: HPE Cray EX System (University Community Computing), Tech. rep., NSF National Center for Atmospheric Research, Boulder, CO, 10.5065/qx9a-pg09, 2023.



- Diao, X., Stössel, A., Chang, P., Danabasoglu, G., Yeager, S. G., Gopal, A., Wang, H., and Zhang, S.: On the Intermittent Occurrence of Open-Ocean Polynyas in a Multi-Century High-Resolution Preindustrial Earth System Model Simulation, *Journal of Geophysical Research: Oceans*, 127, e2021JC017672, <https://doi.org/10.1029/2021JC017672>, 2022.
- Dong, Y., Pauling, A. G., Sadai, S., and Armour, K. C.: Antarctic Ice-Sheet Meltwater Reduces Transient Warming and Climate Sensitivity Through the Sea-Surface Temperature Pattern Effect, *Geophysical Research Letters*, 49, e2022GL101249, <https://doi.org/10.1029/2022GL101249>, 2022.
- Dong, Y., Polvani, L. M., and Bonan, D. B.: Recent Multi-Decadal Southern Ocean Surface Cooling Unlikely Caused by Southern Annular Mode Trends, *Geophysical Research Letters*, 50, e2023GL106142, <https://doi.org/10.1029/2023GL106142>, 2023.
- EUMETSAT OSI SAF: Global Sea Ice Concentration Interim Climate Data Record Release 3 - DMSP, https://doi.org/10.15770/EUM_SAF_OSI_0014, 2022.
- EUMETSAT OSI SAF: Sea Ice Concentration Climate Data Record Release 3.1 - Multimission, https://doi.org/10.15770/EUM_SAF_OSI_0023, 2025.
- Ferreira, D., Marshall, J., Bitz, C. M., Solomon, S., and Plumb, A.: Antarctic Ocean and Sea Ice Response to Ozone Depletion: A Two-Time-Scale Problem, *Journal of Climate*, 28, 1206–1226, <https://doi.org/10.1175/JCLI-D-14-00313.1>, 2015.
- Ford, R.: r-ford/mesacclip-antarctic-sea-ice: Preprint version, <https://doi.org/10.5281/zenodo.23242986>, 2026.
- Ford, R. R. and Rose, B. E. J.: A Southern Ocean Multidecadal Oscillator Forced by Deep Convection, *Geophysical Research Letters*, 53, e2025GL120643, <https://doi.org/10.1029/2025GL120643>, 2026.
- Goosse, H., Dalaiden, Q., Feba, F., Mezzina, B., and Fogt, R. L.: A drop in Antarctic sea ice extent at the end of the 1970s, *Communications Earth & Environment*, 5, 1–11, <https://doi.org/10.1038/s43247-024-01793-x>, 2024.
- Hartmann, D. L.: The Antarctic ozone hole and the pattern effect on climate sensitivity, *Proceedings of the National Academy of Sciences*, 119, e2207889119, <https://doi.org/10.1073/pnas.2207889119>, 2022.
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmonds, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., De Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R. J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., de Rosnay, P., Rozum, I., Vamborg, F., Villaume, S., and Thépaut, J.-N.: The ERA5 global reanalysis, *Quarterly Journal of the Royal Meteorological Society*, 146, 1999–2049, <https://doi.org/10.1002/qj.3803>, 2020.
- Holland, M. M., Landrum, L., Kostov, Y., and Marshall, J.: Sensitivity of Antarctic sea ice to the Southern Annular Mode in coupled climate models, *Climate Dynamics*, 49, 1813–1831, <https://doi.org/10.1007/s00382-016-3424-9>, 2017.
- Holmes, C. R., Bracegirdle, T. J., Holland, P. R., Stroeve, J., and Wilkinson, J.: Brief communication: New perspectives on the skill of modelled sea ice trends in light of recent Antarctic sea ice loss, *The Cryosphere*, 18, 5641–5652, <https://doi.org/10.5194/tc-18-5641-2024>, 2024.
- Huang, B., Thorne, P. W., Banzon, V. F., Boyer, T., Chepurin, G., Lawrimore, J. H., Menne, M. J., Smith, T. M., Vose, R. S., and Zhang, H.-M.: Extended Reconstructed Sea Surface Temperature, Version 5 (ERSSTv5): Upgrades, Validations, and Intercomparisons, *Journal of Climate*, 30, 8179–8205, <https://doi.org/10.1175/JCLI-D-16-0836.1>, 2017.
- Irving, D. and Simmonds, I.: A New Method for Identifying the Pacific–South American Pattern and Its Influence on Regional Climate Variability, *Journal of Climate*, 29, 6109–6125, <https://doi.org/10.1175/JCLI-D-15-0843.1>, 2016.



- Jüling, A., Dijkstra, H. A., Hogg, A. M., and Moon, W.: Multidecadal variability in the climate system: phenomena and mechanisms, *The European Physical Journal Plus*, 135, 506, <https://doi.org/10.1140/epjp/s13360-020-00515-4>, 2020.
- 445 Jüling, A., von der Heydt, A., and Dijkstra, H. A.: Effects of strongly eddying oceans on multidecadal climate variability in the Community Earth System Model, *Ocean Science*, 17, 1251–1271, <https://doi.org/10.5194/os-17-1251-2021>, 2021.
- Kohyama, T. and Hartmann, D. L.: Antarctic Sea Ice Response to Weather and Climate Modes of Variability, *Journal of Climate*, 29, 721–741, <https://doi.org/10.1175/JCLI-D-15-0301.1>, 2016.
- Latif, M. and Keenlyside, N. S.: A perspective on decadal climate variability and predictability, *Deep Sea Research Part II: Topical Studies*
- 450 in *Oceanography*, 58, 1880–1894, <https://doi.org/10.1016/j.dsr2.2010.10.066>, 2011.
- Li, S., Liu, W., Zhang, L., Seviour, W. J. M., and Schmidt, G. A.: Stratospheric Ozone Depletion Causes Southern Ocean Surface Cooling, *Geophysical Research Letters*, 53, e2025GL120200, <https://doi.org/10.1029/2025GL120200>, 2026.
- Liu, W.: Simulated Antarctic sea ice expansion reconciles climate model with observation, *npj Climate and Atmospheric Science*, 8, 1–12, <https://doi.org/10.1038/s41612-024-00881-1>, 2025.
- 455 Lu, S., Marinov, I., and Molodtsov, S.: Linking open-ocean polynyas and deep convection in the Southern Ocean across CMIP6 models, *EGUsphere*, pp. 1–46, <https://doi.org/10.5194/egusphere-2026-3060>, 2026.
- Madden, R. A. and Jones, R. H.: A Quantitative Estimate of the Effect of Aliasing in Climatological Time Series, *Journal of Climate*, 14, 3987–3993, [https://doi.org/10.1175/1520-0442\(2001\)014<3987:AQEOTE>2.0.CO;2](https://doi.org/10.1175/1520-0442(2001)014<3987:AQEOTE>2.0.CO;2), 2001.
- Meehl, G. A., Arblaster, J. M., Bitz, C. M., Chung, C. T. Y., and Teng, H.: Antarctic sea-ice expansion between 2000 and 2014 driven by
- 460 tropical Pacific decadal climate variability, *Nature Geoscience*, 9, 590–595, <https://doi.org/10.1038/ngeo2751>, 2016.
- Meehl, G. A., Yang, D., Arblaster, J. M., Bates, S. C., Rosenbloom, N., Neale, R., Bacmeister, J., Lauritzen, P. H., Bryan, F., Small, J., Truesdale, J., Hannay, C., Shields, C., Strand, W. G., Dennis, J., and Danabasoglu, G.: Effects of Model Resolution, Physics, and Coupling on Southern Hemisphere Storm Tracks in CESM1.3, *Geophysical Research Letters*, 46, 12408–12416, <https://doi.org/10.1029/2019GL084057>, 2019.
- 465 Meier, W., Fetterer, F., Windnagel, A., Stewart, J. S., and Stafford, T.: NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration, Version 6, <https://doi.org/10.7265/B18J-Z797>, 2026.
- Mo, K. C. and Higgins, R. W.: The Pacific–South American Modes and Tropical Convection during the Southern Hemisphere Winter, *Monthly Weather Review*, 126, 1581–1596, [https://doi.org/10.1175/1520-0493\(1998\)126<1581:TPSAMA>2.0.CO;2](https://doi.org/10.1175/1520-0493(1998)126<1581:TPSAMA>2.0.CO;2), 1998.
- Mohrmann, M., Heuzé, C., and Swart, S.: Southern Ocean polynyas in CMIP6 models, *The Cryosphere*, 15, 4281–4313, <https://doi.org/10.5194/tc-15-4281-2021>, 2021.
- 470 Morioka, Y., Manabe, S., Zhang, L., Delworth, T. L., Cooke, W., Nonaka, M., and Behera, S. K.: Antarctic sea ice multi-decadal variability triggered by Southern Annular Mode and deep convection, *Communications Earth & Environment*, 5, 1–11, <https://doi.org/10.1038/s43247-024-01783-z>, 2024.
- Möller, J., Dommenges, D., and Semenov, V. A.: The Annual Peak in the SST Anomaly Spectrum, *Journal of Climate*, 21, 2810–2823, <https://doi.org/10.1175/2007JCLI2025.1>, 2008.
- Pauling, A. G., Bitz, C. M., Smith, I. J., and Langhorne, P. J.: The Response of the Southern Ocean and Antarctic Sea Ice to Freshwater from Ice Shelves in an Earth System Model, *Journal of Climate*, 29, 1655–1672, <https://doi.org/10.1175/JCLI-D-15-0501.1>, 2016.
- Polvani, L. M., Banerjee, A., Chemke, R., Doddridge, E. W., Ferreira, D., Gnanadesikan, A., Holland, M. A., Kostov, Y., Marshall, J., Seviour, W. J. M., Solomon, S., and Waugh, D. W.: Interannual SAM Modulation of Antarctic Sea Ice Extent Does Not Account



- 480 for Its Long-Term Trends, Pointing to a Limited Role for Ozone Depletion, *Geophysical Research Letters*, 48, e2021GL094871,
<https://doi.org/10.1029/2021GL094871>, 2021.
- Prieto, G. A.: The Multitaper Spectrum Analysis Package in Python, *Seismological Research Letters*, 93, 1922–1929,
<https://doi.org/10.1785/0220210332>, 2022.
- Purich, A., Cai, W., England, M. H., and Cowan, T.: Evidence for link between modelled trends in Antarctic sea ice and underestimated
485 westerly wind changes, *Nature Communications*, 7, 10409, <https://doi.org/10.1038/ncomms10409>, 2016a.
- Purich, A., England, M. H., Cai, W., Chikamoto, Y., Timmermann, A., Fyfe, J. C., Frankcombe, L., Meehl, G. A., and Arblaster, J. M.:
Tropical Pacific SST Drivers of Recent Antarctic Sea Ice Trends, *Journal of Climate*, 29, 8931–8948, <https://doi.org/10.1175/JCLI-D-16-0440.1>, 2016b.
- Rayner, N. A., Parker, D. E., Horton, E. B., Folland, C. K., Alexander, L. V., Rowell, D. P., Kent, E. C., and Kaplan, A.: Global analyses
490 of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century, *Journal of Geophysical Research: Atmospheres*, 108, <https://doi.org/10.1029/2002JD002670>, 2003.
- Roach, L. A. and Polvani, L. M.: Persistent Antarctic Sea Ice Biases in CMIP6 Models in spite of the Recent Decadelong Sharp Decline,
Journal of Climate, 39, 1669–1679, <https://doi.org/10.1175/JCLI-D-25-0477.1>, 2026.
- Roach, L. A., Dörr, J., Holmes, C. R., Massonnet, F., Blockley, E. W., Notz, D., Rackow, T., Raphael, M. N., O’Farrell,
495 S. P., Bailey, D. A., and Bitz, C. M.: Antarctic Sea Ice Area in CMIP6, *Geophysical Research Letters*, 47, e2019GL086729,
<https://doi.org/10.1029/2019GL086729>, 2020.
- Roach, L. A., Mankoff, K. D., Romanou, A., Blanchard-Wrigglesworth, E., Haine, T. W. N., and Schmidt, G. A.: Winds and Meltwa-
ter Together Lead to Southern Ocean Surface Cooling and Sea Ice Expansion, *Geophysical Research Letters*, 50, e2023GL105948,
<https://doi.org/10.1029/2023GL105948>, 2023.
- 500 Rye, C. D., Marshall, J., Kelley, M., Russell, G., Nazarenko, L. S., Kostov, Y., Schmidt, G. A., and Hansen, J.: Antarc-
tic Glacial Melt as a Driver of Recent Southern Ocean Climate Trends, *Geophysical Research Letters*, 47, e2019GL086892,
<https://doi.org/10.1029/2019GL086892>, 2020.
- Santer, B. D., Wigley, T. M. L., Boyle, J. S., Gaffen, D. J., Hnilo, J. J., Nychka, D., Parker, D. E., and Taylor, K. E.: Statistical significance of
trends and trend differences in layer-average atmospheric temperature time series, *Journal of Geophysical Research: Atmospheres*, 105,
505 7337–7356, <https://doi.org/10.1029/1999JD901105>, 2000.
- Schmidt, G. A., Romanou, A., Roach, L. A., Mankoff, K. D., Li, Q., Rye, C. D., Kelley, M., Marshall, J. C., and Busecke, J. J. M.:
Anomalous Meltwater From Ice Sheets and Ice Shelves Is a Historical Forcing, *Geophysical Research Letters*, 50, e2023GL106530,
<https://doi.org/10.1029/2023GL106530>, 2023.
- Schneider, D. P., Deser, C., and Okumura, Y.: An assessment and interpretation of the observed warming of West Antarctica in the austral
510 spring, *Climate Dynamics*, 38, 323–347, <https://doi.org/10.1007/s00382-010-0985-x>, 2012.
- Screen, J. A.: Sudden increase in Antarctic sea ice: Fact or artifact?, *Geophysical Research Letters*, 38,
<https://doi.org/10.1029/2011GL047553>, 2011.
- Shu, Q., Wang, Q., Song, Z., Qiao, F., Zhao, J., Chu, M., and Li, X.: Assessment of Sea Ice Extent in CMIP6 With Comparison to Observations
and CMIP5, *Geophysical Research Letters*, 47, e2020GL087965, <https://doi.org/10.1029/2020GL087965>, 2020.
- 515 Silvano, A., Narayanan, A., Catany, R., Olmedo, E., González-Gambau, V., Turiel, A., Sabia, R., Mazloff, M. R., Spira, T., Haumann, F. A.,
and Naveira Garabato, A. C.: Rising surface salinity and declining sea ice: A new Southern Ocean state revealed by satellites, *Proceedings
of the National Academy of Sciences*, 122, e2500440122, <https://doi.org/10.1073/pnas.2500440122>, 2025.



- Simpkins, G. R., Ciasto, L. M., Thompson, D. W. J., and England, M. H.: Seasonal Relationships between Large-Scale Climate Variability and Antarctic Sea Ice Concentration, *Journal of Climate*, 25, 5451–5469, <https://doi.org/10.1175/JCLI-D-11-00367.1>, 2012.
- 520 Singh, H. A., Polvani, L. M., and Rasch, P. J.: Antarctic Sea Ice Expansion, Driven by Internal Variability, in the Presence of Increasing Atmospheric CO₂, *Geophysical Research Letters*, 46, 14 762–14 771, <https://doi.org/10.1029/2019GL083758>, 2019.
- Swart, N. C. and Fyfe, J. C.: The influence of recent Antarctic ice sheet retreat on simulated sea ice area trends, *Geophysical Research Letters*, 40, 4328–4332, <https://doi.org/10.1002/grl.50820>, 2013.
- Swart, N. C., Martin, T., Beadling, R., Chen, J.-J., Danek, C., England, M. H., Farneti, R., Griffies, S. M., Hattermann, T., Hauck, J.,
525 Haumann, F. A., Jüling, A., Li, Q., Marshall, J., Muilwijk, M., Pauling, A. G., Purich, A., Smith, I. J., and Thomas, M.: The Southern Ocean Freshwater Input from Antarctica (SOFIA) Initiative: scientific objectives and experimental design, *Geoscientific Model Development*, 16, 7289–7309, <https://doi.org/10.5194/gmd-16-7289-2023>, 2023.
- Turner, J., Hosking, J. S., Marshall, G. J., Phillips, T., and Bracegirdle, T. J.: Antarctic sea ice increase consistent with intrinsic variability of the Amundsen Sea Low, *Climate Dynamics*, 46, 2391–2402, <https://doi.org/10.1007/s00382-015-2708-9>, 2016.
- 530 Wang, P., Solomon, S., Deser, C., Thompson, D., and Diffenbaugh, N.: Antarctic Ozone Loss Shapes Surface Cooling Pattern and Climate Sensitivity, <https://doi.org/10.21203/rs.3.rs-8544146/v1>, 2026.
- Wills, R. C. J., Dong, Y., Proistosescu, C., Armour, K. C., and Battisti, D. S.: Systematic Climate Model Biases in the Large-Scale Patterns of Recent Sea-Surface Temperature and Sea-Level Pressure Change, *Geophysical Research Letters*, 49, e2022GL100011, <https://doi.org/10.1029/2022GL100011>, 2022.
- 535 Zhang, L., Delworth, T. L., Cooke, W., and Yang, X.: Natural variability of Southern Ocean convection as a driver of observed climate trends, *Nature Climate Change*, 9, 59–65, <https://doi.org/10.1038/s41558-018-0350-3>, 2019.
- Zhu, Z., Liu, J., Liu, Y., Martin, T., Song, M., Yang, C.-Y., Chai, W., and Yang, Q.: Implications of Realistic Antarctic Ice Shelf Basal Melting During 2006–2016 on Southern Ocean Climate, *Geophysical Research Letters*, 53, e2025GL119237, <https://doi.org/10.1029/2025GL119237>, 2026.