Author Comments

Seasonality and scenario dependence of rapid Arctic sea ice loss events in CMIP6 simulations

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Anonymous Referee #2

The authors of this study investigate Arctic Rapid Ice Loss Events (RILEs) in the CMIP6 ensemble, including their frequency through the year, dependence on emission scenario, and possible preconditioning conditions. The manuscript is well written, the figures high quality, and the methodology sound and well described. I think this paper will be an important contribution to the literature and have only minor suggestions before it should be published.

Reply. We thank the reviewer for his/her constructive comments on the manuscript and we provide our replies below for specific comments.

Specific Comments:

Variability results: (Line 259 and elsewhere). The impact of variability on the frequency or probability of RILEs is a major result, yet there are no figures showing variability. The value of the large ensembles in this analysis is the ability to look at variability for a single model and how that relates to RILEs, something you can't do with the CMIP6 multi-model ensemble. A figure like 5b and 5c but with variability at RILE start would be beneficial. Additionally, Figure S5 may be relevant for the main manuscript and something you could add as a panel to Figure 1. I think you should spend a bit more time on this result since in your conclusions you list it (Line 307-309) but no main figures show larger variability in a model leads to more RILES.

Reply. Thank you for highlighting the importance of variability in relation to RILE frequency and probability. We agree that variability is a key result, and we already include discussion about variability in section 3.3 (lines 215,216,220,225, and 235-240). While a new figure illustrating SIE variability at the onset of RILEs may not capture its importance, we agree that Fig. S5 provides valuable insights and is relevant in the main manuscript.

Action. We will add Fig. S5 to the main text as this figure is referred several times in Section ' 3.3 Mean State Influence on RILE Occurrence '.

Figure 4: The order of how you refer to the panels in the text is confusing and you should consider re-ordering them.

Reply. We appreciate the reviewer's feedback regarding the arrangement of the figures to improve the readability of Section 3, which was also raised by reviewer 1. We agree that separating panels e–g from Figures 4 and 5 and combining them into a new figure will help streamline the presentation of the results better.

Action. We will:

1. Remove panels e–g from Figures 4 and 5 and create a new combined figure (Fig.C3a and b).
2. Rearrange the order of the figures in the text to ensure consistency and logical flow. For instance, we will mention Figure 6 in its appropriate place in Section 3.3, after the discussion of Figure 4a in Section 3.2.

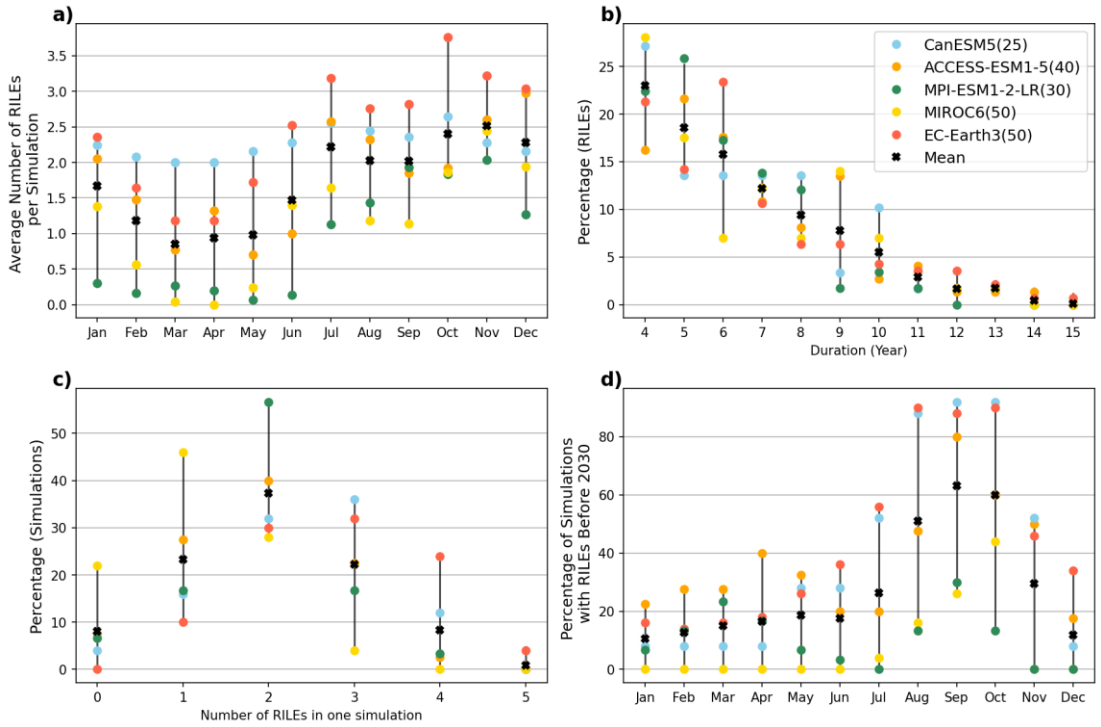

Figure C3a. *RILEs characteristics in 5 CMIP6 LE: (a) average number of RILEs per simulation, (b) percentage of SRILEs as a function of their duration in years, (c) percentage of SRILEs per simulation, and (d) percentage of simulations having at least one RILE occurrence before 2030 in each month under the high warming scenario SSP5-8.5.*

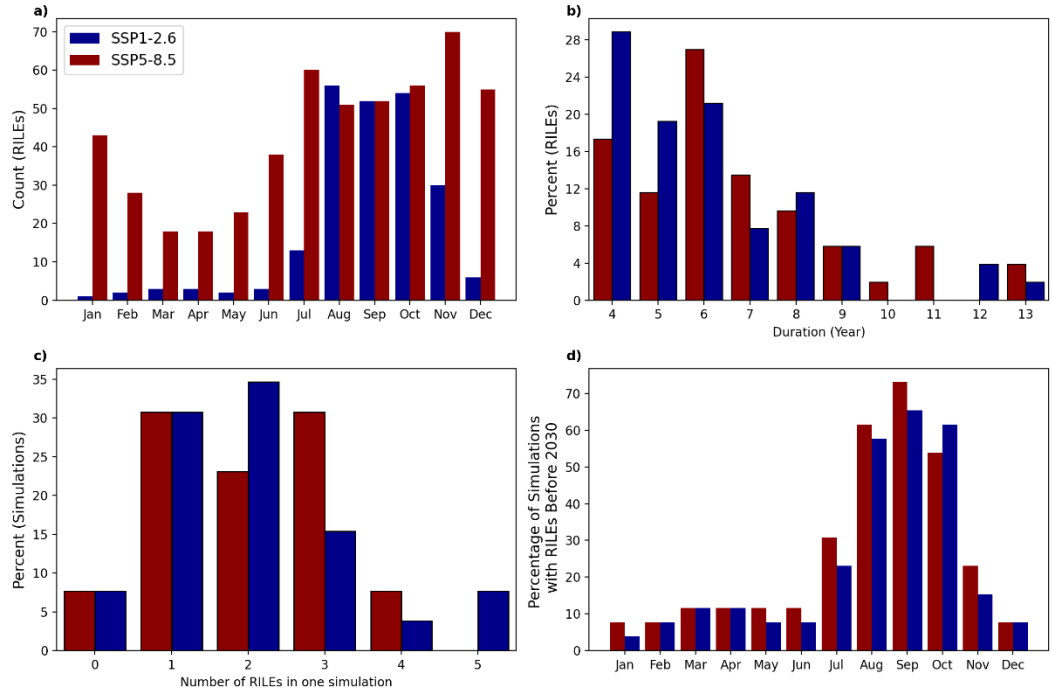

Figure C3b. *RILEs characteristics in the CMIP6 multi-model ensemble: (a) total Number of RILEs, (b) percentage of SRILEs as a function of their duration in years, (c)percentage of SRILEs per simulation, and (d) percentage of simulations having at least one RILE occurrence before 2030 in each month under the high warming scenario SSP5-8.5 (red) and under the low warming scenario SSP1-2.6 (blue).*

Figure 5: I do not understand what 5f and 5g are showing and 5f is not referenced in text anywhere. Maybe this figure or panels from this figure could be in the supplementary material.

Reply. We thank the reviewer for pointing out the lack of clarity and lack of interpretation. However, we think that these results should stay in the main manuscript. We will update Figure 5 by removing panels e-g and creating a new combined figure that more clearly presents the characteristics of RILEs (Fig. C3a). The updated figure will show the percentage of the average number of RILEs per simulation (a), the duration of RILEs (b), the number of RILEs in one simulation (c), and the percentage of simulations with RILEs before 2030 (d) for each model, highlighting the variability between models in a clearer way. Panel b) of Figure C3a represents the percentage of SRILEs as a function of their duration, while Panel c) shows the percentage of simulations as a function of the number of SRILEs occurring in one simulation.

Action. We propose to add the following discussion in Section "3.2 Probability of occurrence of RILEs":

"SRILEs most commonly last between 4 and 6 years, although some events can persist for up to 15 years (Fig. C3a, b)). Notably, when SRILEs extend beyond 10 years, they often directly lead to ice-free conditions. Additionally, these results appear to be consistent across models, indicating that the duration of SRILEs is not strongly model-dependent.

The maximum number of SRILEs observed in a single simulation is 5, which only occurs in the EC-Earth3 model—known for its large internal sea ice varability (Fig. C3a, c)). For most simulations, 2 SRILEs are the most likely outcome. Interestingly, while a majority of simulations feature at least one SRILE, the results show significant model disparities: EC-Earth3 predicts SRILEs in 100% of its simulations, consistent with its high variability. In contrast, MIROC6 simulations mostly show only 1 SRILE or, in many cases, no SRILEs at all, highlighting a weaker tendency for rapid sea ice loss events in this model."

Figure 6: If RILEs initiate more often after a period of stable SIE trends, does this imply that the SIV would still have a negative trend during this period. So the ice is thinning but not changing extent? Can you add some text about what's going on with SIV during these periods?

Reply. We appreciate the question regarding SIV behavior during periods when SIE trends are stable, particularly in relation to the initiation of RILEs. To address this, we analyze the SIV trends during these periods (Fig. C6). Specifically, we investigate whether periods of stability in SIE coincide with "hidden sea ice loss," characterized by a decline in SIV despite the absence of shrinking in SIE. Such conditions may create a more vulnerable state for the sea ice, potentially increasing the likelihood of RILEs in subsequent years. We identify all periods of SIE stability accompanied by combined SIV loss and analyze the SIE trends following these periods. Our results indicate that there is no significant increase in the frequency of RILEs after such "hidden sea ice loss" periods, with only ~12% of subsequent SIE trends falling below -0.3 million km^2 per year (Fig. C6, yellow histogram). This result provides further insight into the preconditions for RILE initiation: a period of stable or positive 10-year SIE trends combined with sea ice volume loss does not appear to increase the probability of a RILE occurring in the subsequent years.

Action. We will keep Fig. 6 as it is in the main text and add the following sentence in Section "3.2 Probability of occurrence of RILEs":

"Furthermore, these periods of no sea ice loss combined with a decline of SIV for the same 10-year period does not appear to increase the probability of a RILE occurring in the subsequent years (not shown)."

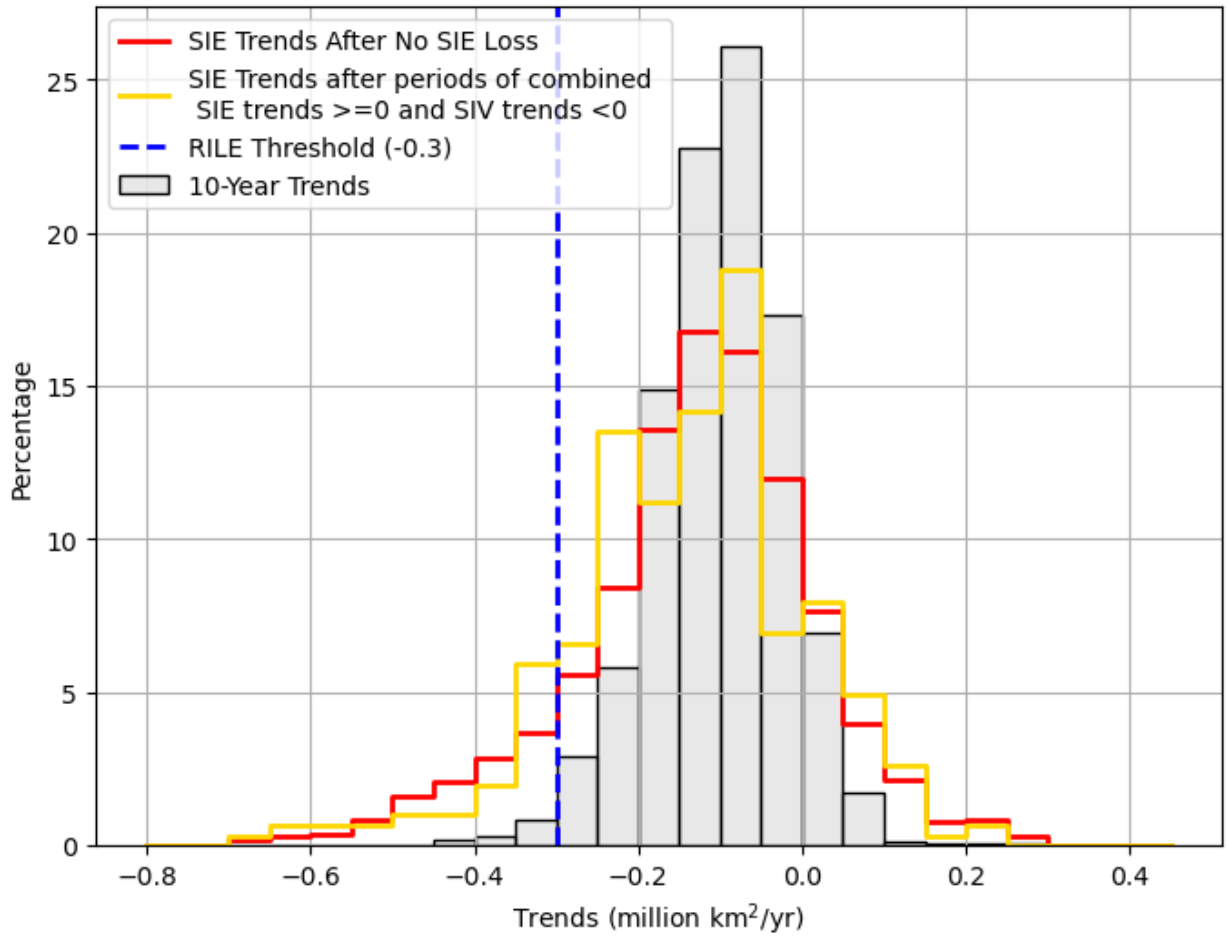

Figure C6. Distribution of all possible 10-year Arctic September SIE trends (grey) for the CMIP6 multi-model ensemble under the SSP5-8.5 scenario, from 2015 to consistently ice-free conditions. The trends are computed using a 5-year running mean of the SIE time series. The red outline represents SIE trends following periods of stability, where stability is defined as a 10-year period with zero or positive SIE trends. The yellow outline corresponds to SIE trends following periods where 10-year SIE trends are equal to or greater than zero, combined with 10-year negative trends in SIV. The blue dashed line indicates the threshold of -0.3 million km^2/yr, used to define RILEs (see Section 2.3 for details).

Line 2 and Line 8: “practically ice free” and “nearly ice free” is awkward. Just define “ice free” and go with it.

Reply. We believe it is important to retain "practically" in this context, as the definition used here refers to an ice-free Arctic as 1 million km^2 of sea ice or less, rather than the complete disappearance of sea ice. This choice reflects the diversity of "ice-free Arctic" definitions in literature (see Jahn et al., 2024).

Action. We will replace "nearly" with "practically" in the sentence in line 8 to provide greater clarity.

Line 6-7: This is a confusing sentence because if you're looking from start of satellite era, why are you listing 2000-2008 rates?

Reply. We are listing 2001-2008 because it is the largest observed rate since the beginning of the satellite observing period.

Action. To clarify this sentence, we will rephrase it as follows:

"The extreme sea ice loss associated with RILEs in climate models exceeds any observed rates of sea ice loss since the start of the satellite era, including the largest observed rate of -0.28 million km2 per year during 2001–2008."

Line 7: what is "it"? Maybe say "As such, there could be a much faster transition…"

Action. We will rephrase "As such, it could lead to a much faster transition…" in "As such, there could be a much faster transition…"

Lines 101-104: This description of these conversions is confusing. Maybe use equations instead of text? Also, shouldn't grid cell area come in here?

Reply. Thank you for pointing this out. We agree that the original description was too brief and could cause confusion. We will not use equations to maintain consistency with the rest of the text but will ensure that the methodology is precise.

Action. We will clarify the text to better describe how we computed sea ice volume (SIV) when it was not directly available, explicitly including the role of grid cell area in these calculations. We will update the text as follows:

"We also analyzed SIV, labeled as sivoln in the CMIP6 output. If SIV was not available, we computed it from sea ice thickness (SIT), labeled as sivol (grid cell-averaged ice thickness) or sithick (sea ice thickness averaged over the ice-covered portion of a grid cell) in the CMIP6 output. When only sithick was provided, we calculated the SIV by multiplying sithick by sea ice concentration (SIC) and the grid cell area."

Line 138-139: What do you mean a RILE can manifest as one year event or several years? This sentence sounds like you mean the metric by the Döscher and Koenigk since that's the last you discussed, and that's a one-year definition.

Reply. We are referring to Döscher and Koenigk's definition.

Action. We will replace "As such," by "According to their definition," in lines 138-139.

Line 140: Is a RICE substantively different than a RILE? Why not include this in the other metrics described?

Reply. The acronym RICE might be confusing as the events described are specific to a region and season.

Action. To address this, we will remove the acronym that was only used here.

Line 203: What is "a period"? Is it a single year where the 10-year previous trend was positive or zero? This sentence needs clarification.

Action. We will clarify to" period of no sea ice loss" to match the previous definition (i.e., a 10-year period with a zero or positive SIE trend)

Line 295: The sentence where you say the percentage goes from 62-96% is confusing and should be clarified.

Action. We will rephrase the sentence as follows:

"For the CMIP6 multi-model ensemble, the percentage of models experiencing at least one RILE varies depending on the month of the year, ranging from 62% in the month with the fewest models simulating a RILE to 96% in the month with the most models simulating a RILE. Notably, every model shows at least one RILE during the analysis period."