Analysis of Early-Warning Signals for Arctic Summer Sea Ice Loss

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Abstract

The rapid loss of Arctic Sea Ice (ASI) in the last decades is one of the most evident manifestations of anthropogenic climate change. A transition to an ice-free Arctic during summer would impact climate and ecosystems, both regionally and globally. The identification of Early-Warning Signals (EWSs) for the loss of the summer ASI could provide important insights into the state of the Arctic region. We collect and analyze CMIP6 model runs that reach ASI-free conditions (area below 10ˆ6 kmˆ2) in September. Despite the high inter-model spread, with the range for the date of an ice-free summer spanning around 100 years, the evolution of the summer ASI area right before reaching ice-free conditions is strikingly similar across the CMIP6 models. When looking for EWSs for summer ASI loss, we observe a significant increase in the variance of the ASI area before reaching ice-free conditions. This behavior is detected in the majority of the models, and also averaged over the ensemble. We find no increase in the 1-year-lag autocorrelation in model data, possibly due to the multiscale characteristics of climate variability, which can mask changes in serial correlations. However, in the satellite-inferred observations, increases in both variance and 1-year-lag autocorrelation have recently been revealed.

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The Arctic region is threatened by global warming

The Arctic region is experiencing the fastest increase in surface temperature in response to global warming, with the rapid loss of ASI in the last decades being one of the most evident manifestations of anthropogenic climate change.

A transition to a summer ice-free Arctic would impact climate and ecosystems, both regionally and globally, leading to:

- changes in ocean, wind, and atmospheric circulation patterns, especially the jet stream [1-6]
- imbalances in Arctic marine ecosystems [7]
- a decline in food security for Indigenous communities [8]
- possibilities for new commercial trade routes [8] with potentially detrimental consequences [9]

The analysis and identification of EWSs for the loss of the summer ASI are of crucial importance to gather insights into the state of the Arctic region.

Methods

In our study, we exclude the models that completely lose the ASI too early in the past and the ones that do not reach the threshold for an ASI-free summer.

In some model runs, the ASI area fluctuates around the 10^6 km^2-threshold for a few years after the ASI is completely lost for the first time. Therefore, we smooth the time series using a 20-year centered moving average and determine the year of complete ASI loss from the smoothed curve.

We calculate the ASI area variance and 1-year-lag autocorrelation in Fig. 1 on a 25-year-long moving window on the residuals, obtained by subtracting a 20-year centered moving average smoothing to the data from each model.

We estimate the sensitivity of the ASI area as the rate of ASI loss per degree of warming before the complete loss of the September ASI (Fig. 2). We fit the ASI area curves using the least squares method and calculate the rate of loss per degree of warming as the slope of the fitting line.

In order to gather ensemble information on the behavior of the models as they approach summer ASI-free conditions, we shift the curves from the different models in time prior to averaging (Figs. 1 & 3). In this way, all the models completely lose the September ASI in the same year.

State of the art

Most of the Earth System Models in the CMIP6 ensemble [10] are inaccurately reproducing the observed ASI area evolution since 1979 [11]. Partly due to differences in the respective sea ice modules incorporated in the different models and to uncertainties related to climate feedbacks, the inter-model spread is high. Also, the models do not constrain the date of an ice-free summer to less than 100 years, and only about 25% of them are in the plausible range for ASI loss per degree of warming [11]. However, the evolution of the summer ASI area right before reaching ice-free conditions is strikingly similar across the models.

Increasing summer ASI area fluctuations are expected with future global warming

Averaged over the ensemble, and for most of the models, we observe a significant increase in the variance of the summer ASI area before ice-free conditions are reached.

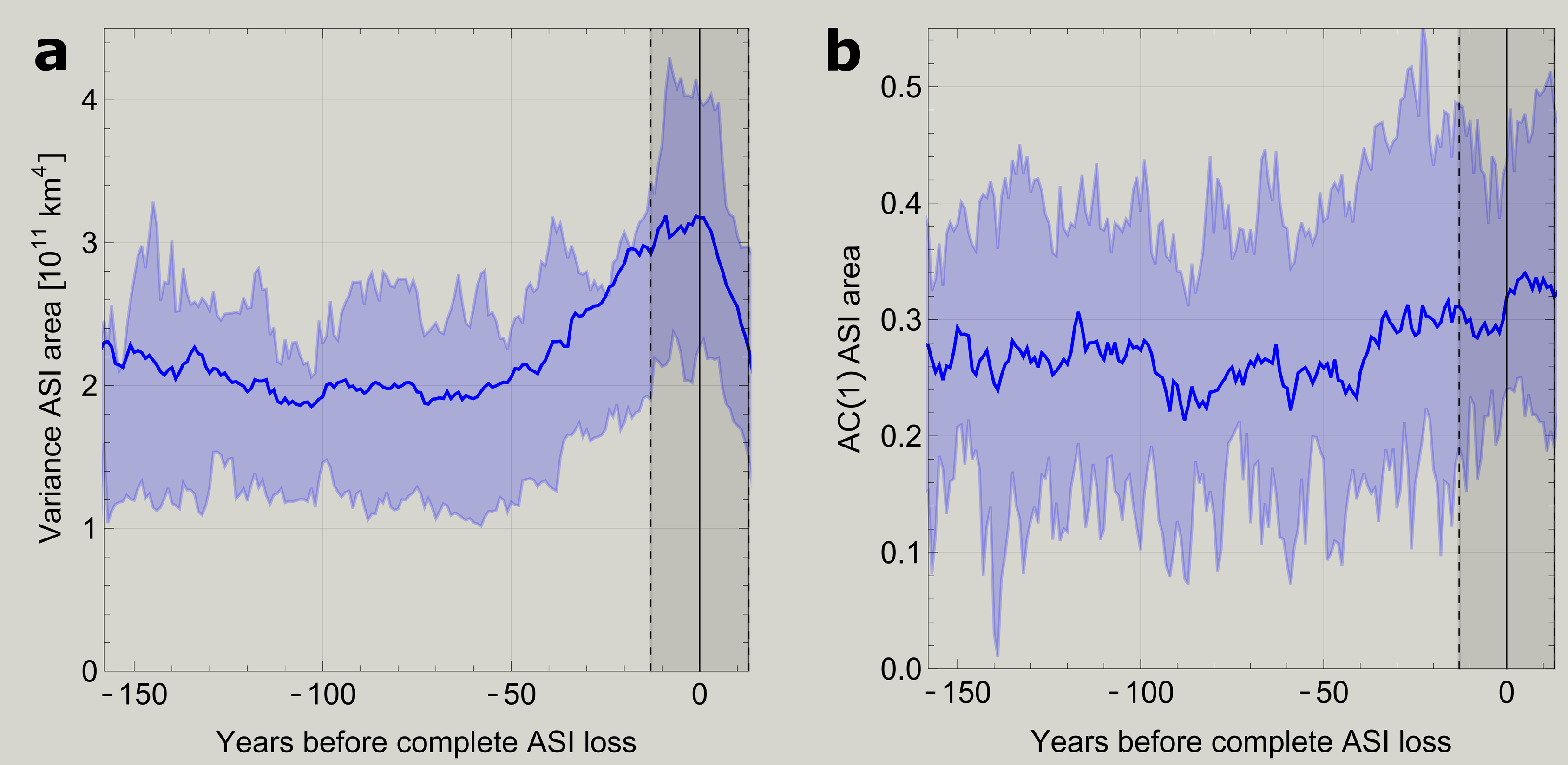

Figure 1. **Summer ASI area variance and 1-year-lag autocorrelation in the CMIP6 ensemble.** **(a)** Averaged variance of the September ASI area for the CMIP6 models (solid blue line) calculated within a window length of $w = 25$ years. The filled blue area denotes the values between the 25th percentile (lower line) and the 75th percentile (upper line). The models are shifted in time such that they all completely lose the summer ASI in year 0 (see Methods section for details). The filled grey area corresponds to one standard deviation of the average year of ice loss derived from the models (2045±13 years). **(b)** Same as **(a)** but for 1-year-lag autocorrelation.

The increasing fluctuations imply that in the near future there will likely be events with very low or no summer ASI at all followed by periods of regrowth, showing an apparent short-term recovery of the ASI loss.

Even though increasing fluctuations and variance are typical EWSs of tipping points, it has been shown that EWSs also precede non-catastrophic transitions [12].

We find no clear increase in the 1-year-lag autocorrelation in model data, possibly due to the multiscale characteristics of climate variability, which can mask changes in serial correlations [13, 14]. However, in the satellite-inferred observations, increases in both variance and 1-year-lag autocorrelation have recently been revealed [15].

References and data availability

Available at the following link: `https://tinyurl.com/bdz3m32z`

Possible reasons for increasing fluctuations

In the CMIP6 ensemble, the average sensitivity of ASI area to Global Mean Temperature (GMT) is higher for the last degree of warming before reaching ASI-free summers than in the temperature range between 1 and 2°C before reaching ASI-free summers (Fig. 2). As the sensitivity of the ASI area to GMT increases, we expect to see increasingly large fluctuations in the ice area in response to natural climate variability [16].

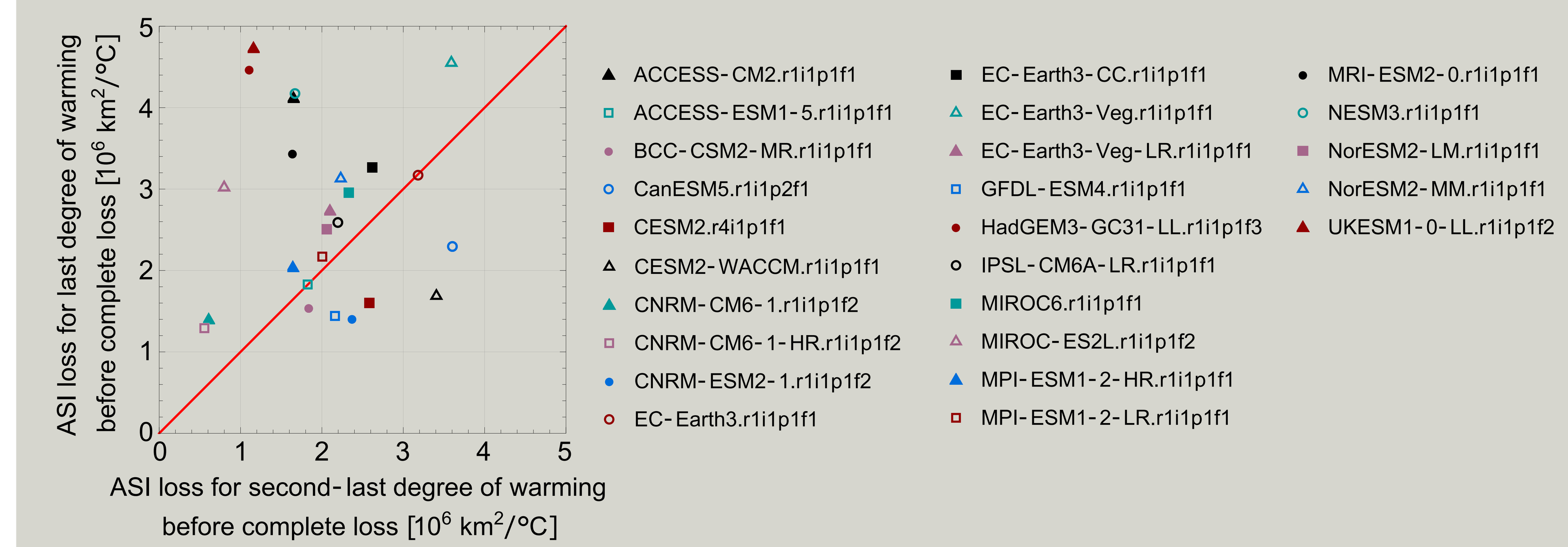

Figure 2. **Sensitivity of the summer ASI area in the CMIP6 ensemble.** Rate of ASI loss for the last degree of warming before the complete loss of the summer ASI, against ASI loss for the second-last degree of warming before the complete loss of the September ASI for all CMIP6 models. The majority of the models (18 out of 25) show an increased loss for the last degree of warming.

Simultaneously with the increase in the variance (which begins approximately 50 years before complete summer ASI loss), we observe both a decline in the September ASI thickness and in the fraction of the ASI edge connected to the land, both averaged over the ensemble and for most of the models (Fig. 3). The thinning and detachment from the land might be contributing factors to the increasing fluctuations in the ASI area.

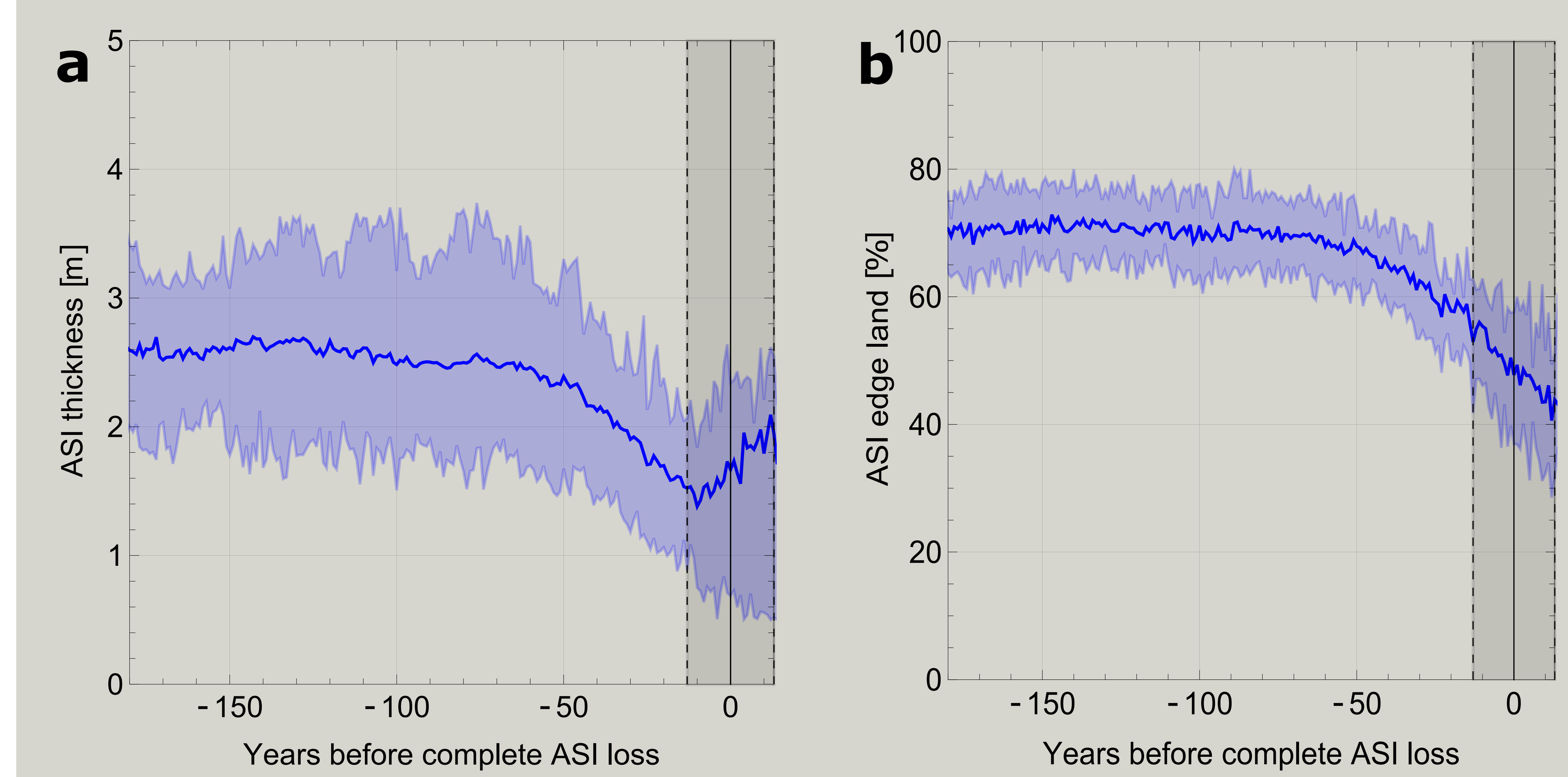

Figure 3. **Summer ASI thickness and fraction of the ASI edge connected to the land in the CMIP6 ensemble.** **(a)** Averaged September ASI thickness for the CMIP6 models (solid blue line). The filled blue area denotes the values between the 25th percentile (lower line) and the 75th percentile (upper line). The models are shifted in time such that they all completely lose the summer ASI in year 0 (see Methods section for details). The filled grey area corresponds to one standard deviation of the average year of ice loss derived from the models (2045±13 years). **(b)** Same as **(a)** but for the fraction of the ASI edge connected to the land.

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