Increasing Fluctuations and Sensitivity of Arctic Summer Sea-Ice Cover Are Expected With Future Global Warming

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Abstract

Every year, the area of the Arctic sea-ice decreases in the boreal spring and summer and reaches its yearly minimum in the early autumn. The continuous satellite-based time series shows that the September area has decreased from 4.5*10ˆ6 kmˆ2 in 1979, to 2.8*10ˆ6 kmˆ2 in 2020. The decline has been approximately linear in global mean surface temperature, with a rate of loss of 2.7*10ˆ6 kmˆ2 per degree C of global warming. In the CMIP6 ensemble, however, we find that the majority of the models that reach an Arctic sea-ice free state in the SSP585 runs shows an accelerated loss of sea-ice for the last degree of warming compared to the second last degree of warming, which implies an increased sensitivity of the sea-ice to temperature changes. Both in the observational and CMIP6 data, we find that the decline in September sea-ice area is approximately proportional to the area north of which the zonal average temperature in spring and summer is lower than a critical threshold Tc. The Arctic amplification implies that the zonally averaged temperatures increase relative to the global temperatures, and with rates increasing with latitude. Linear extrapolation of the zonally averaged temperatures predicts that, with further warming, the September sea-ice area will depend non-linearly on global temperature, the sensitivity will increase and the September sea-ice area may become less that 1*10ˆ6 kmˆ2 for global warming between 0.9 and 1.6 degrees C above the current temperature. As a result of accelerated sea-ice loss, the average evolution of the sea-ice area among the CMIP6 models before the loss of the summer sea-ice shows an increase in the year-to-year fluctuations in minimum ice cover in the next decade. This implies exceptional accumulation of extreme events with very low or no sea-ice at all even before the final loss of the sea-ice. Likewise, an apparent short-term recovery of the sea-ice loss might be observable due to the increasing fluctuations.

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References and data availability

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Abstract

Every year, the area of the Arctic sea-ice (ASI) decreases in the boreal spring and summer and reaches its yearly minimum in the early autumn. The decline has been approximately linear in global mean surface temperature (GMT).

However, in the CMIP6 ensemble, the average sensitivity of the ASI area to GMTs increases as the models approach ice-free summers.

As a result of accelerated ASI loss, the average evolution of the ASI area among the CMIP6 models before the loss of the summer ASI shows an increase in the year-to-year fluctuations in minimum ice cover in the next decade.

The Arctic region is threatened by global warming

The Arctic region is experiencing the most rapid 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 [1-3]
- imbalances in Arctic marine ecosystems
- a decline in food security for Indigenous communities [4]
- possibilities for new commercial trade routes [4] with potentially detrimental consequences [5]

The area covered by ASI in summer is generally assumed to decline linearly with the increasing GMTs at the surface [6-10]. These results are mostly based on Earth System Model (ESM) experiments, while only some studies incorporate observations.

In the CMIP6 ensemble [11], however, we find that the majority of the models that reach a ASI free state in the SSP585 runs show an accelerated loss of ASI for the last degree of warming compared to the second last degree of warming, which implies an increased sensitivity of the ASI to temperature changes.

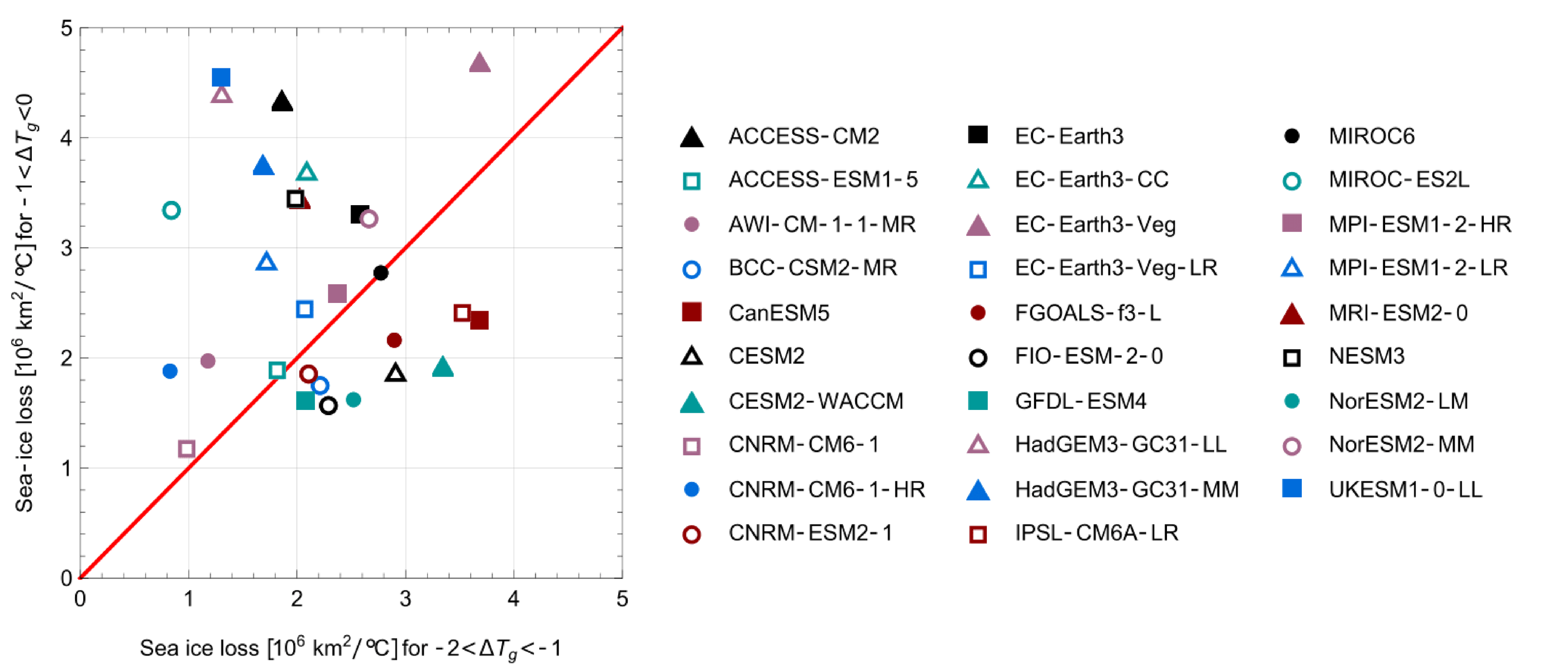

Figure 1. **Sensitivity of the ASI area for the CMIP6 model simulations.** Rate of ASI loss for the last degree of warming before complete loss of the summer ASI for the first time against ASI loss for the second-last degree of warming before complete loss of the summer ASI for the first time for the CMIP6 models considered. The majority of the models (19 out of 29) show an increased loss for the last degree of warming.

State of the art

Most of the Earth System Models in the CMIP6 ensemble are inaccurately reproducing the observed ASI area evolution since 1979 [12]. Partly due to differences in the respective ASI 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 [12].

The prediction of future ASI loss requires quantifying the sensitivity of the ASI area to changes in GMT, which depend on several coupled feedbacks. While we are currently observing an approximately linear dependence between September ASI area and GMT, there is no *a priori* reason to expect that the sensitivity will remain constant under further warming.

Prediction of future sea-ice loss

Motivated by the intrinsic relationship between the ASI area and temperature found in the simplest models [13-15], where the ASI area is defined as the area above the isotherm of a critical temperature threshold, we propose an analogous dependence in both the CMIP6 models and the real climate system.

We find proportionality between September ASI area and the area of the latitudes in the northern hemisphere where the January-to-September mean temperature is below a critical temperature T_c also in observational data and most CMIP6 models.

Moreover, we find linear dependence of the zonal average temperature and the GMT in both observations and future projections (in all the CMIP6 models).

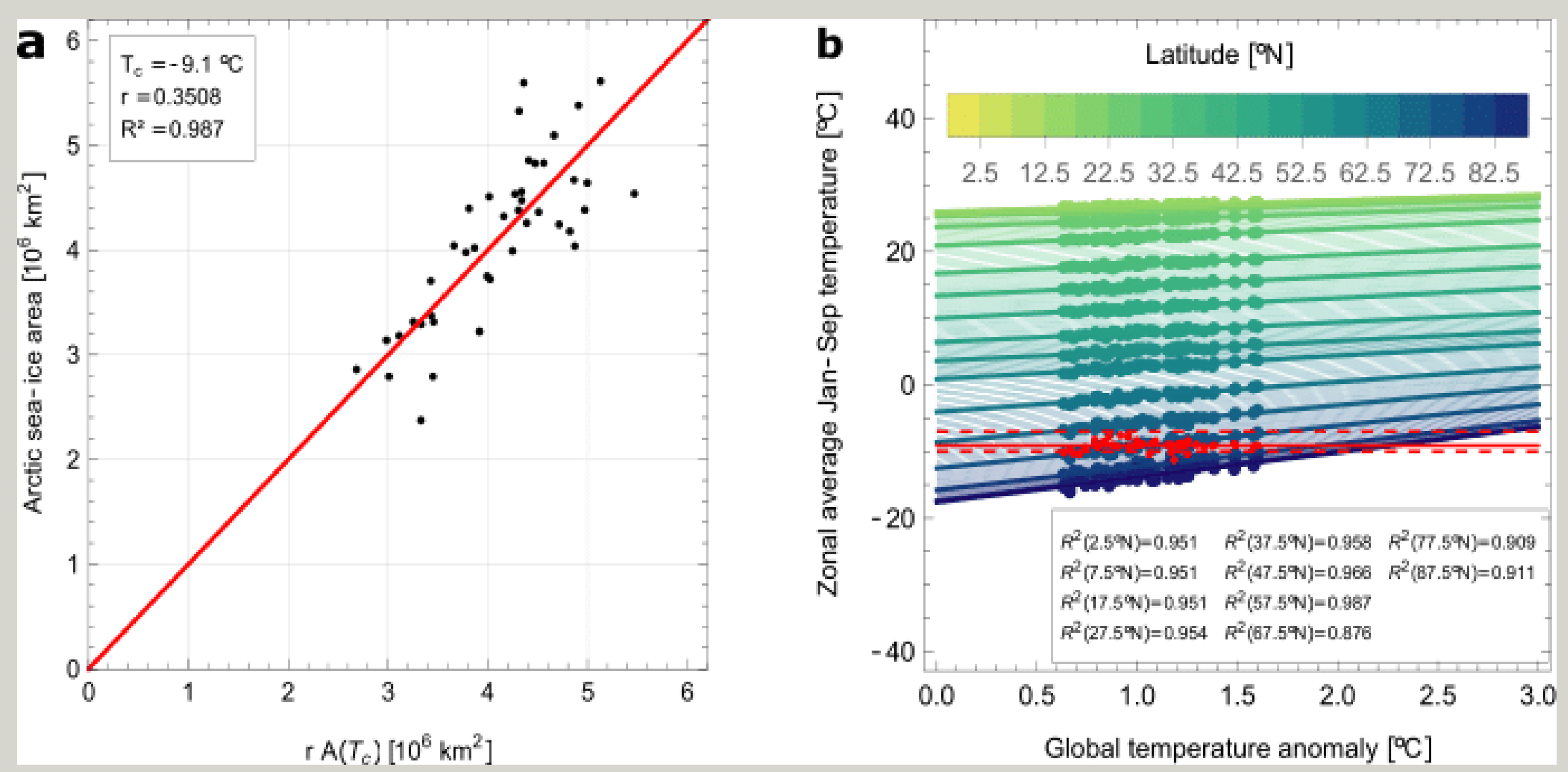

Figure 2. **Observed and extrapolated summer ASI area (1979-2020) and temperature.** **(a)** Approximate relationship between observed September ASI area and the area defined by latitudes in the northern hemisphere where the January-to-September mean temperature is below the critical temperature $T_c = -9.1$°C. **(b)** Observed and extrapolated zonally averaged temperatures (Jan-Sep) against GMT anomalies from the equator to the north pole. The red lines denote the critical temperature T_c (solid) with 95% confidence range (dashed). The red points are the critical temperature values obtained from the satellite data for September ASI area.

We extrapolate the linear trend of the zonal temperature into the future, and we combine it with the relationship between zonally averaged temperatures and ASI area. We obtain a prediction for ice-free conditions based on the observational record, with data from CMIP6 verifying the assumptions.

Arctic summer sea-ice loss will accelerate in coming decades

Ice-free conditions (area below 10^6 km^2) are predicted for global warming between 0.9 and 1.6°C above the current GMT and the results suggest increased sensitivity of the ASI with higher temperatures.

Despite the high inter-model spread, the majority of the models show a strikingly similar evolution of the ASI area before ice-free conditions, with accelerated ASI loss and increased sensitivity close to the ice-free state. We observe a significant increase of the variance before reaching ice-free conditions both averaged over the CMIP6 ensemble, and for most models.

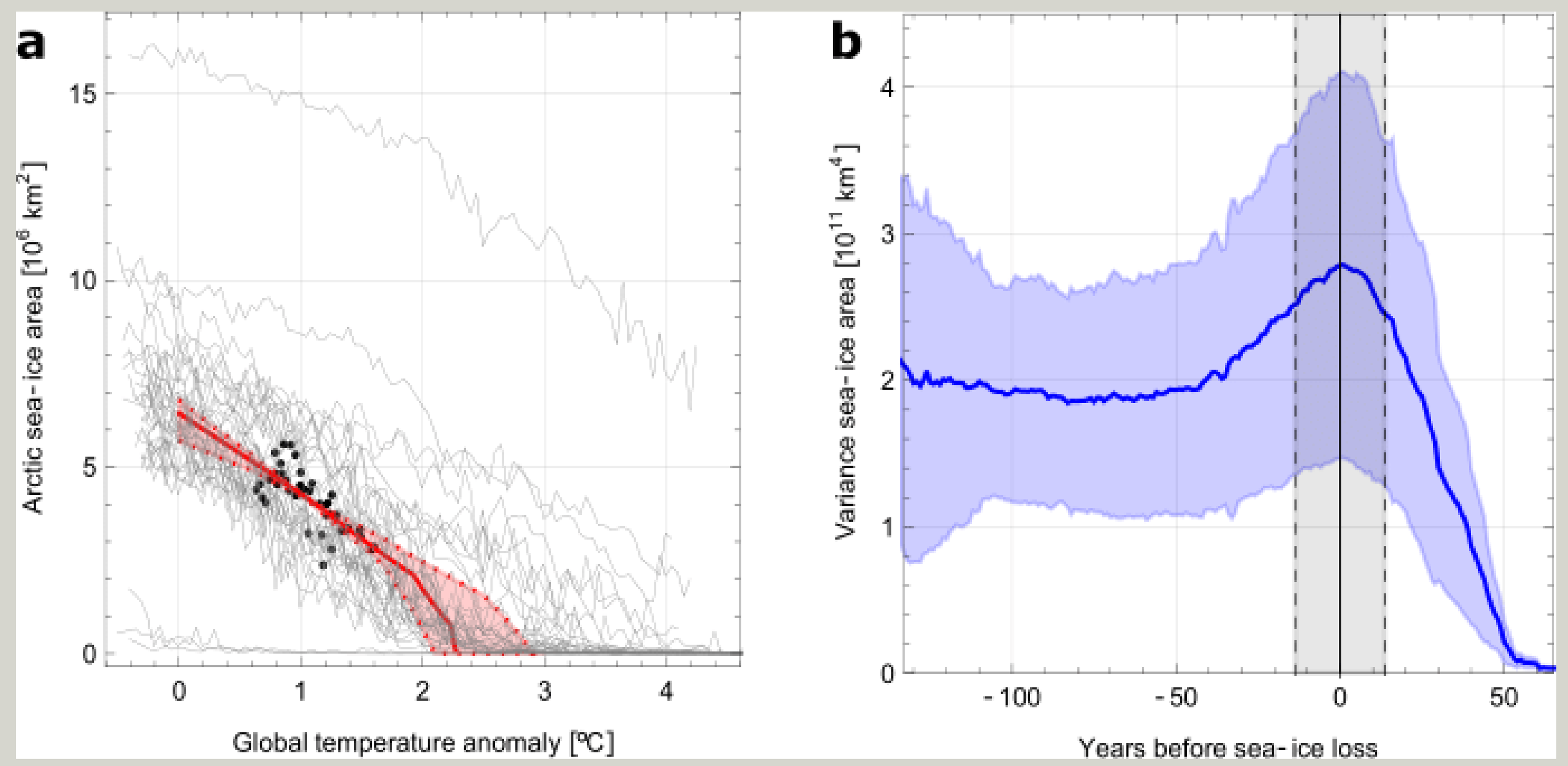

Figure 3. **Observed and extrapolated summer ASI area (1979-2020) and fluctuations of ASI area in CMIP6 models.** **(a)** Projected dependence between GMT anomalies and the September ASI area (red area). The September ASI areas for CMIP6 models are shown as the grey curves. **(b)** Averaged variance of the ASI area in the CMIP6 models (solid blue line) calculated within a window length of $w = 50$ years with standard deviation (filled blue area). The models are shifted in time so that the ASI is fully lost for the first time in year 0. The filled grey area is the standard deviation for the year of ice loss ($\sigma = 14$ yrs).

Methods

The linear dependence of the zonal average temperature and the global temperature anomaly T_a for each latitude θ shown in figure 2b can be described by the equation $T(\theta) = a(\theta)T_a + b(\theta)$. Let T_c be the critical temperature threshold represented by the red solid line in figure 2b. The solution to the equation $T(\theta) = T_c$, gives the value of $\theta = \theta_{\text{edge}}$ used in the equation:

$$A(T_c) = 2\pi R^2_{\text{Earth}} \int_{\theta_{\text{edge}}}^{\pi/2} \cos(\theta) \mathrm{d}\theta$$

to calculate the area $A(T_c)$ that best approximates the ASI area A_{ASI} for a given value of T_a, except for a factor r. Finally, using the equation $A_{\text{ASI}} = rA(T_c)$, we get the value A_{ASI} for the ASI area used to get the prediction in figure 3a for the chosen T_a. The uncertainty is calculated by applying this same method to the dashed lines in figure 2b (95% confidence range for T_c).

The variance in figure 3b is calculated on a 50-year long moving window on the residuals for the ASI area, obtained by subtracting a 20-year centered moving-average smoothing to the data from each model. The variance curves from the different models are then shifted in time so that all the models lose the ASI for the first time in the same year and are then averaged. This allows us to identify ensemble information on the behavior of the models as the threshold for a summer sea-ice-free Arctic is approached.

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