Reasons for the intermodel spread of simulated Arctic sea-ice sensitivities

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1 Aim of this study

Arctic September sea-ice area retreats linearly with cumulative CO_2 emissions [1].

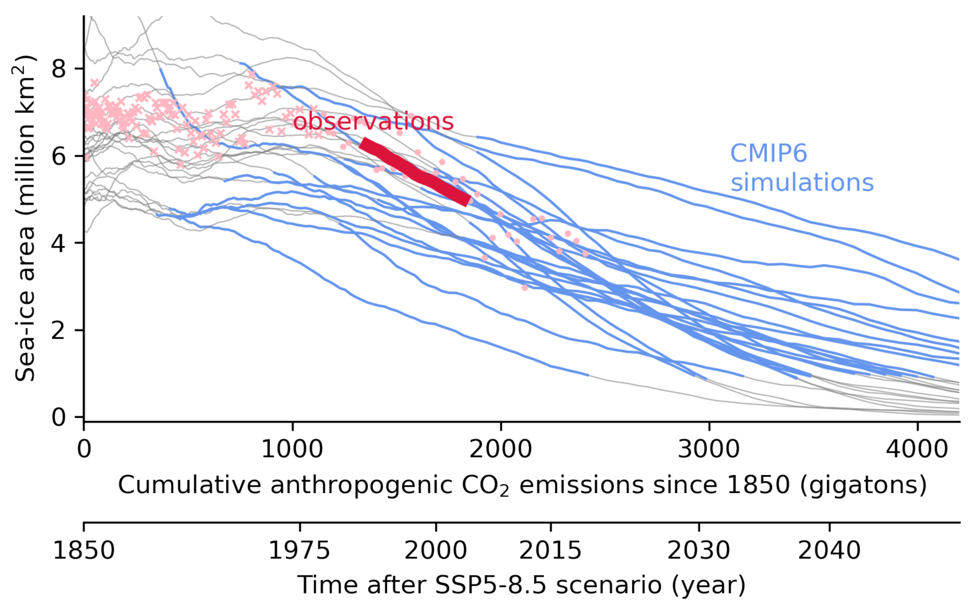

Figure 1.1: **Relation between Arctic September sea-ice area (SIA) and cumulative anthropogenic CO_2 emissions**. The pink markers represent the yearly observational data of SIA as a function of cumulative CO_2 emissions or time (crosses for the Walsh dataset [2] and dots for the NSIDC Bootstrap dataset [3]). The thick red line indicates the 30-year moving average of observed SIA. The thin grey lines represent the 30-year moving average from CMIP6 model simulations (historical and SSP585 run). Blue lines indicate those parts of the CMIP6 simulations that lie within the transition period, which starts after the sea-ice area drops below 90% of the simulated average sea-ice area between 1850 and 1900 and ends when there is less than 1 million km² of sea ice left.

Models generally underestimate the observed sea-ice sensitivity $\frac{d\,SIA}{d\,CO_2}$ and there is a large intermodel spread.

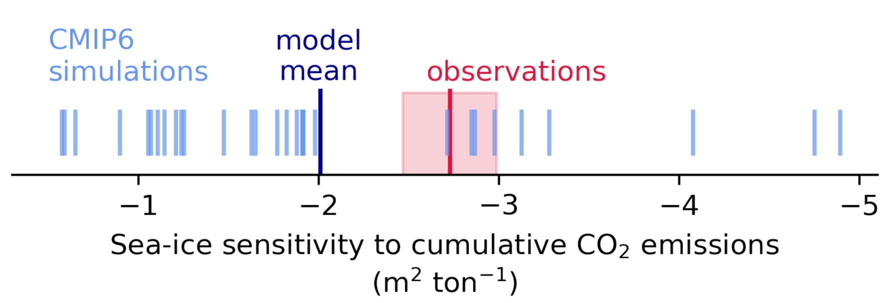

Figure 1.2: **The sea-ice sensitivity as simulated in CMIP6 and observed**. The blue lines indicate the simulated values and the red line represents the observations with satellites. The red shaded area indicated the observational uncertainty. The dark blue line indicates the mean sea-ice sensitivity across all CMIP6 models.

The aim of this study is to investigate the reasons for the intermodel spread of the simulated Arctic September sea-ice sensitivity in CMIP6 model output.

Take home messages

1. **The simulated intermodel spread of sea-ice sensitivity is strongly linked to the simulation of the incoming longwave radiation in the Arctic.**
2. **If the simulation of Arctic temperature rise was more accurate, the intermodel spread of sea-ice sensitivity would strongly be reduced.**
3. **Clouds play a minor role for the intermodel spread of simulated incoming longwave radiation.**

2 Possible reasons for intermodel spread of simulated sea-ice sensitivities

Notz and Stroeve (2016) showed that $\frac{d\,SIA}{d\,CO_2} \propto \frac{d\,F_{LW,in}}{d\,CO_2}$, meaning that models with a high sea-ice sensitivity also simulate a high sensitivity of incoming longwave radiation in the Arctic $F_{LW,in}$ to CO_2 emissions [1].

Therefore, it is worth investigating the reasons for the intermodel spread of $\frac{d\,F_{LW,in}}{d\,CO_2}$.

$F_{LW,in}$ is mainly driven by clouds, temperature and moisture [4,5]. It can be assumed that the relative humdity is constant, thus changes in moisture are represented by temperature changes.

In the following, we investigate the impact of the representation of **clouds** and **temperature** on the intermodel spread of $\frac{d\,F_{LW,in}}{d\,CO_2}$ and therefore also $\frac{d\,SIA}{d\,CO_2}$.

2a Representation of clouds only plays a minor role.

How do we test the cloud's contribution to the intermodel spread?

Besides the usual simulation of incoming longwave radiation, models also calculate the incoming longwave radiation that would be simulated if there were no clouds. This parameter is called clear-sky incoming longwave radiation $F_{LW,in,clear}$ whereas the original parameter is called all-sky incoming longwave radiation $F_{LW,in,all}$. Their relation is $F_{LW,in,all} = F_{LW,in,clear} + CRE$, where CRE is the cloud radiative effect.

What do we find?

The sensitivities of the clear-sky and the all-sky $F_{LW,in}$ are highly correlated. Both intermodel spreads are similarly large.

The sensitivity of $F_{LW,in,clear}$ is almost equally higly correlated to the sea-ice sensitivity as the sensitivity of $F_{LW,in,all}$.

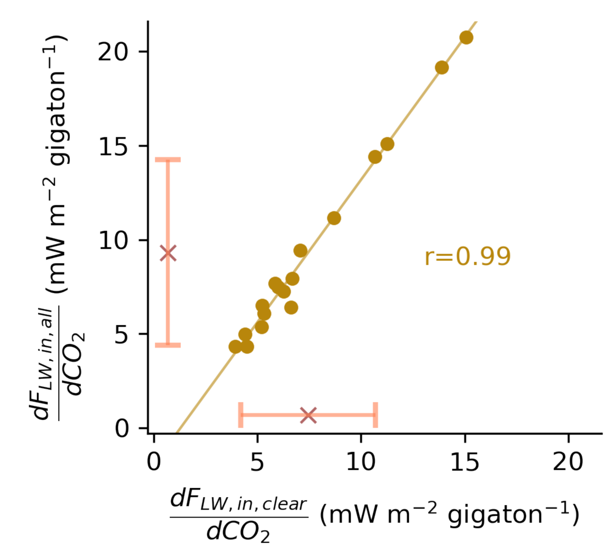

Figure 2.1: **Relation between $\frac{d\,F_{LW,in,all}}{d\,CO_2}$ and $\frac{d\,F_{LW,in,clear}}{d\,CO_2}$**. Each dot represents $\frac{d\,F_{LW,in,all}}{d\,CO_2}$ in a particular model as a function of $\frac{d\,F_{LW,in,clear}}{d\,CO_2}$ in the same model. The yellow line represents the linear regression line. The correlation r is indicated. The crosses represent the intermodel mean of $\frac{d\,F_{LW,in,all}}{d\,CO_2}$ and $\frac{d\,F_{LW,in,clear}}{d\,CO_2}$ and the bars indicate the standard deviation.

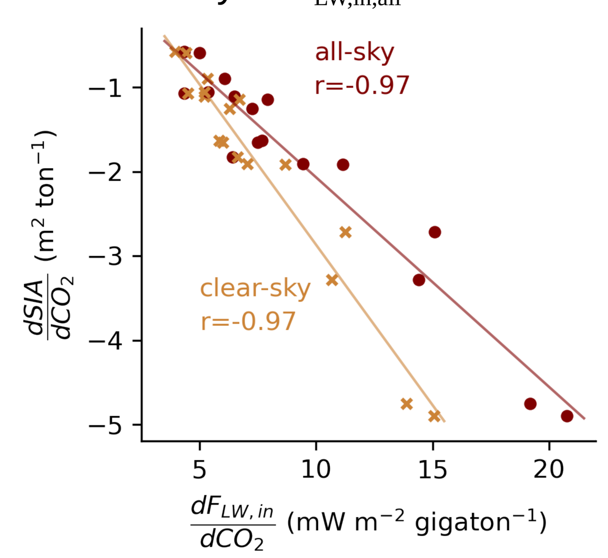

Figure 2.2: **Relation between $\frac{d\,F_{LW,in,all}}{d\,CO_2}$ and $\frac{d\,SIA}{d\,CO_2}$ as well as between $\frac{d\,F_{LW,in,clear}}{d\,CO_2}$ and $\frac{d\,SIA}{d\,CO_2}$**. Each dot represents $\frac{d\,SIA}{d\,CO_2}$ in a particular model as a function of $\frac{d\,F_{LW,in,all}}{d\,CO_2}$ / $\frac{d\,F_{LW,in,clear}}{d\,CO_2}$ in the same model. The lines represent the linear regression lines. The correlations r are indicated.

What does that mean?

The different representation of clouds across the models does not contribute substantially to the intermodel spread of simulated Arctic sea-ice sensitivity.

2b Representation of temperature plays a major role.

How do we test the temperature's contribution to the intermodel spread?

The sea-ice sensitivity can be split at the impact of temperature: $\frac{d\,SIA}{d\,CO_2} = \frac{d\,T}{d\,CO_2} \cdot \frac{d\,SIA}{d\,T}$, where the global mean temperature is considered. However, we also consider the Arctic temperature (mean temperature north of 80°N) which then means that $\frac{d\,SIA}{d\,CO_2} = \frac{d\,T}{d\,CO_2} \cdot \frac{d\,T_{arct}}{d\,T} \cdot \frac{d\,SIA}{d\,T_{arct}}$. The Arctic amplification is represented by $\frac{d\,T_{arct}}{d\,T}$. In the following, we investigate how well $\frac{d\,SIA}{d\,T}$ and $\frac{d\,SIA}{d\,T_{arct}}$ are simulated.

What do we find?

The relative error between the observed and the simulated sea-ice sensitivities to warming reduces strongly when only the Arctic is considered.

If the Arctic warming is simulated correctly, the response of sea ice is represented fairly well and only contributes little to the intermodel spread of the overall sea-ice sensitivity.

When considering the sensitivity to global warming, the Arctic amplification is incorporated in the sensitivity. Therefore, we can conclude that the representation of the Arcitc amplification stronlgy contributes to the intermodel spread.

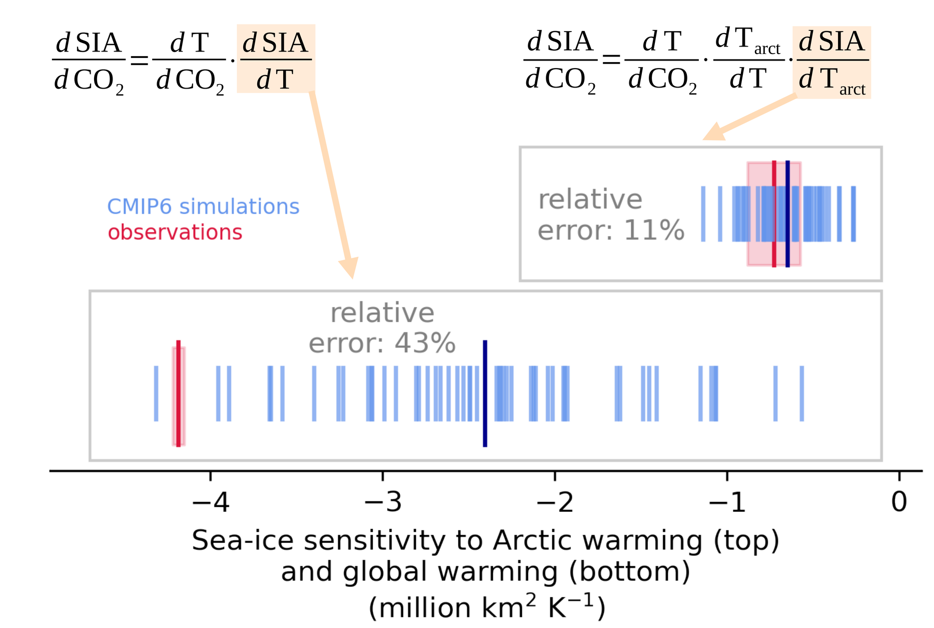

Figure 2.3: **The sea-ice sensitivity to warming as simulated in CMIP6 and observed**. The blue lines indicate the simulated values and the red lines represent the observations with satellites. The red shaded areas indicate the observational uncertainties. The dark blue lines indicate the mean sea-ice sensitivities to warming across all CMIP6 models. The upper lines represent the sensitivity to Arctic warming and the lower lines represent the sensitivity to global warming.

What does that mean?

The different representation of the Arctic temperature evolution and the Arctic amplification in particular are primarily responsible for the intermodel spread of simulated Arctic sea-ice sensitivity.

References:
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[2] Walsh, J. E., W. L. Chapman, F. Fetterer, and J. S. Stewart, 2019: Gridded Monthly Sea Ice Extent and Concentration, 1850 Onward, Version 2. National Snow and Ice Data Center, https://doi.org/10.7265/jj4s-tq79.
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[5] Stephens, G. L., M. Wild, P. W. Stackhouse, T. L'Ecuyer, S. Kato, and D. S. Henderson, 2012: The Global Character of the Flux of Downward Longwave Radiation. Journal of Climate, 25 (7), 2329 – 2340, https://doi.org/10.1175/JCLI-D-11-00262.1.

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