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Key Points:
- We find it is unlikely that September Arctic sea ice vanishes for 1.5°C global warming
- September sea ice might vanish for 2.0°C global warming, but observational uncertainty prevents a conclusive statement
- Internal variability causes a range of about ±0.2°C to the global warming magnitude at which September Arctic sea ice is lost

Supporting Information:
- Supporting Information S1

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Arctic Sea Ice in a 1.5°C Warmer World

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Abstract We examine the seasonal cycle of Arctic sea ice in scenarios with limited future global warming. To do so, we analyze two sets of observational records that cover the observational uncertainty of Arctic sea ice loss per degree of global warming. The observations are combined with 100 simulations of historical and future climate evolution from the Max Planck Institute Earth System Model Grand Ensemble. Based on the high-sensitivity observations, we find that Arctic September sea ice is lost with low probability ($P \approx 10\%$) for global warming of +1.5°C above preindustrial levels and with very high probability ($P > 99\%$) for global warming of +2°C above preindustrial levels. For the low-sensitivity observations, September sea ice is extremely unlikely to disappear for +1.5°C warming ($P \ll 1\%$) and has low likelihood ($P \approx 10\%$) to disappear even for +2°C global warming. For March, both observational records suggest a loss of 15% to 20% of Arctic sea ice area for 1.5°C to 2°C global warming.

1. Introduction

Arctic sea ice has been declining rapidly in the past few decades, with the strongest decrease observed during late summer (e.g., Cavalieri & Parkinson, 2012; Simmonds, 2015; Stroeve et al., 2012). As the observed loss of sea ice is tightly coupled to increasing global-mean air temperature (Gregory et al., 2002; Li et al., 2013; Mahlstein & Knutti, 2012; Notz & Stroeve, 2015; Ridley et al., 2012; Winton, 2011) and thus to cumulative anthropogenic CO_2 emissions (Notz & Stroeve, 2016), the loss of sea ice can only be stopped if global warming is limited below a certain threshold. To examine the response of the Arctic sea ice cover to such a threshold, we here estimate the seasonal cycle of Arctic sea ice resulting from a limitation of global warming to +1.5°C and to +2.0°C above preindustrial levels, as called for by the Paris Agreement of all Parties of the United Nations Framework Convention on Climate Change (United Nations Framework Convention on Climate Change, 2015).

Our analysis has two overarching aims: First, we want to estimate the mean seasonal cycle of sea ice for a given maximum level of global warming. And second, we want to quantify possible variations around this mean seasonal cycle caused by internal variability. These two aims can only be reached by a combination of the observational record of Arctic sea ice decline with large-scale climate-model simulations. This is because the observational record allows us to estimate the sensitivity of Arctic sea ice to a given global-mean warming, while climate-model simulations allow us to estimate the impact of internal variability. We cannot robustly infer the sensitivity directly from model simulations as they usually simulate a lower sensitivity of Arctic sea ice loss per degree of global warming than has been observed (e.g., Mahlstein & Knutti, 2012; Notz & Stroeve, 2016; Rosenblum & Eisenman, 2017). Note that we focus on the Arctic, as there the sea ice evolution is tightly coupled to atmospheric temperature. Our approach does not work in the Antarctic, where processes related to sea ice dynamics play a major role for the time evolution of the ice cover.

While previous studies of future sea ice evolution are mainly limited to annual mean or summer months (e.g., Mahlstein & Knutti, 2012; Notz & Stroeve, 2016; Rosenblum & Eisenman, 2016; Screen & Williamson, 2017), we give, for different levels of global warming, a complete annual cycle of Arctic sea ice. Using a very large ensemble of simulations, we further estimate its uncertainty due to internal variability. We also specifically address the issue of observational uncertainty.

We start with a brief overview of the model simulations and observational data that we use for our study, explaining in particular how we use the observational data to recalibrate the sensitivity of the modeled sea ice evolution. We then present the resulting seasonal cycle of Arctic sea ice for different levels of global warming and provide maps that show the regional likelihood of ice coverage for a specific global warming.

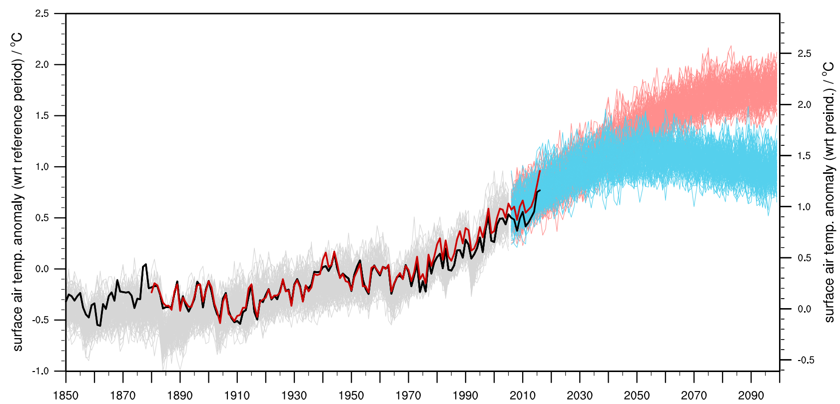

Figure 1. Annual mean global surface air temperature anomalies from observations in black (HadCRUT4) and red (GISTEMP), historical simulations in grey, and the RCP2.6 and RCP4.5 simulations in blue and light red, respectively. Temperature anomalies on the left *y* axis are given relative to the corresponding reference periods of the observations, namely, to the period 1961–1990 for HadCRUT4 and 1950–1989 for GISTEMP. The right *y* axis gives temperature anomalies relative to the long-term mean of a 2,000 year long preindustrial control simulation.

2. Methods

2.1. Model and Observations

For our analysis we use the results from the Max Planck Institute Earth System Model (MPI-ESM) Grand Ensemble, a 100 member strong ensemble of simulations with the MPI-ESM in the low-resolution configuration. The simulations are carried out with model version 1.1, which is an updated version of the model version used for Coupled Model Intercomparison Project Phase 5 (CMIP5). The atmosphere model ECHAM6 has a spectral horizontal resolution of T63 and 47 vertical layers and the ocean model MPIOM has a horizontal resolution of 1.5° and 40 vertical layers. The placement of the ocean model grid poles over Greenland and Antarctica leads to a horizontal resolution of 10 to 50 km in the Arctic Ocean. The performance of the CMIP5 model version has been evaluated against observational records for the atmosphere (Giorgetta et al., 2013), the ocean (Jungclaus et al., 2013), and sea ice (Notz et al., 2013), and the Grand Ensemble simulations have been analyzed in recent studies (e.g., Bittner et al., 2016; Hedemann et al., 2017; Stevens, 2015; Suárez-Gutiérrez et al., 2017).

The simulations of the Grand Ensemble cover the time period 1850 to 2100. For the period 1850 to 2005, the simulations follow the experimental design of the historical simulations of CMIP5 (Taylor et al., 2012). For the years 2006 to 2100, the Grand Ensemble provides 100 ensemble members each for the Representative Concentration Pathways (RCP) 2.6 and for the RCP4.5 scenarios of CMIP5 (Taylor et al., 2012). We use both scenarios for our analysis. The internal variability of the Grand Ensemble lies within one standard deviation of the ensemble mean of all CMIP5 models both for global-mean temperature and sea ice (Olonscheck & Notz, 2017) and is hence in line with the estimate of internal variability of many other models. However, it is of course still possible that the real internal variability of Arctic sea ice is different from the estimate that we use here.

To obtain simulated temperature anomalies relative to preindustrial levels, we subtract the mean global temperature (13.7°C) of a 2,000 year long preindustrial simulation from the time series of global-mean air temperature for each individual model ensemble member (Figure 1).

Simulated Arctic sea ice area is calculated by multiplying for each grid cell the simulated sea ice concentration with the individual grid cell area and adding over the entire Northern Hemisphere. We focus on sea ice area to avoid biases that arise in particular during winter if one uses sea ice extent to compare modelled and observed sea ice coverage (Notz, 2014).

To obtain an estimate of the observed sensitivity of Arctic sea ice, we combine observational estimates of mean global warming with observational estimates of Arctic sea ice area over the past few decades. As observational uncertainty affects these estimates, we use two different data sets both for the estimated global warming and for the estimated evolution of Arctic sea ice. We examined several observational records, and the combinations chosen for this study represent the upper and lower bound of all combinations of these records.

For the first observational estimate of sea ice sensitivity, we combine sea ice area as provided by version 2.2 of the Hadley Centre sea ice and sea surface temperature (HadISST) product (Titchner & Rayner, 2014) with the observational estimate of global-mean temperature evolution from Goddard Institute for Space Studies Surface Temperature Analysis (GISTEMP) (Hansen et al., 2010; GISS Surface Temperature Analysis, NASA Goddard Institute for Space, 2017, https://data.giss.nasa.gov/gistemp/). For the second observational estimate, we merge sea ice area estimates from HadISST and the National Snow and Ice Data Center sea ice index and combine these with the observational estimate of global-mean temperature evolution from HadCRUT4 (Met Office Hadley Centre observations datasets, 2017, https://metoffice.gov.uk/hadobs/hadcrut4/data/current/download.html) (Morice et al., 2012) (see supporting information for details on these products). For all records, we only consider the period 1953 until 2016.

We will refer to the first combination based on GISTEMP and HadISST as the "low-sensitivity observational estimate" and to the second combination based on HadCRUT4 and the merged sea ice product as the "high-sensitivity observational estimate." This is because the first estimate is based on a combination of a data set with comparably high global warming and comparably weak Arctic sea ice loss, resulting in a low estimated sensitivity of the ice cover to global warming. The opposite holds for the second combination of data sets. A linear regression of temperature versus time and of sea ice area versus time suggests that the uncertainty in both quantities amplifies the uncertainty of the inferred sensitivity almost by the same amount and that the observational uncertainty is somewhat increased by our use of the presatellite period before 1979. We nevertheless decided to extend the time series until 1953 because the regressions themselves are more robust for the longer time series. In the main text, we will only show figures for the high-sensitivity observational estimate. The respective figures for the low-sensitivity observational estimate can be found in the supporting information.

For our analyses, we need the estimated temperature anomaly relative to preindustrial levels. To obtain such estimate, we add 0.39°C to the HadCRUT4 time series and 0.36°C to the GISTEMP time series. These values are the mean warming of the period 1961 to 1990 and of the period 1950 to 1989 relative to preindustrial levels in the MPI Grand Ensemble. We use this simulated mean warming to minimize the impact of internal variability when translating the observed anomaly relative to the reference period of the two data sets to an anomaly relative to preindustrial levels. The observed evolution of global-mean temperature lies almost everywhere within the ensemble spread for the entire observational period (Figure 1).

2.2. Bias Correction of Simulated Sea Ice Area

For all months, both the observational records and the Grand Ensemble display a linear relationship between global-mean temperature and Arctic sea ice area. However, for all months the model displays a lower sensitivity than the observations, both for the high-sensitivity observational estimate (Figure 2) and for the low-sensitivity observational estimate (Figure S1).

To correct for this bias while maintaining the modeled internal variability, we calculate for the model ensemble mean and for the observational record the monthly linear regression between Arctic sea ice area and global-mean temperature anomaly. For doing so, we do not need to differentiate between a long-term forced response and possible long-term internal variability, as the linear relationship is independent of the underlying reason for a given warming. For consistency, the regression is based on the observational period 1953 to 2016 both for the model and for the observations. We then subtract the positive or negative bias of the ensemble mean sea ice area as a function of temperature anomaly from the time series of sea ice area in each ensemble member. By construction, this then results in a sea ice sensitivity that is identical between the model ensemble mean and the observational record while maintaining the internal variability of the model simulations. We use these bias-corrected estimates in our analysis of the future seasonal cycle of Arctic sea ice area in section 3.1.

To estimate the regional patterns of Arctic sea ice area, we carry out a similar procedure, but this time we correct the temperature biases. To do so, we calculate for a given sea ice area of the ensemble mean the difference between the modeled and the observed regression lines, giving us an estimate of the temperature bias of our simulations for a given Arctic sea ice area. We correct for this temperature bias when reporting regional patterns of sea ice coverage in section 3.2.

3. Results

3.1. Sea Ice Area as a Function of Global-Mean Surface Temperature

We begin our analysis by calculating for each month both the sensitivity of sea ice area to a given amount of global warming and the amount of warming that is necessary to have a near-ice-free Arctic Ocean. These calculations are based on the linear relationship between global-mean temperature and Arctic sea ice area

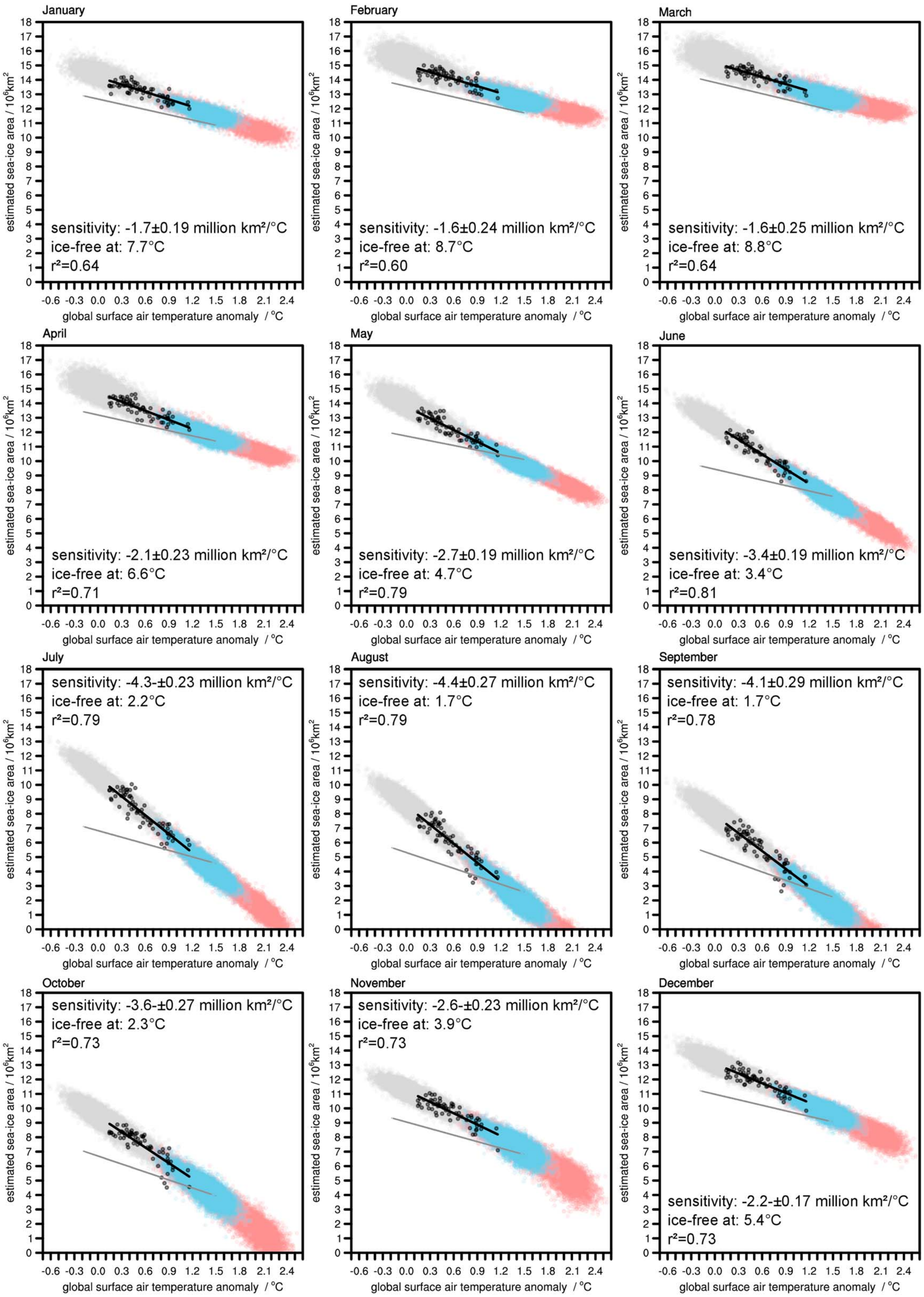

Figure 2. Monthly mean sea ice area for the years 1850–2099 as a function of temperature anomalies relative to preindustrial levels. Black dots indicate the high-sensitivity observational estimate. Historical simulations are shown in gray, RCP2.6 simulations in blue and RCP4.5 simulations in red. The model simulations are bias corrected relative to the high-sensitivity observational record as described in the text. The regression line for the uncorrected model output used for this bias correction is shown in grey. The sensitivity is calculated as the slope of the observed regression line. The temperature anomaly of the regression line for a sea ice area of 1×10^6 km^2 provides an upper bound on the warming at which the Arctic becomes nearly ice free. The coefficient of determination is given with r^2 for each month. See Figure S1 for the low-sensitivity observational estimate.

that we find to hold in all months both in the observations and in the RCP2.6 and RCP4.5 model simulations until the end of this century or until all ice has vanished (see Figures 2 and S1). To prevent a double counting of the historical period in our analysis of individual linear regressions, in the following we restrict our quantitative regression analysis to the RCP4.5 scenario, focusing on March and September as the months of maximum and minimum ice coverage. All our results are barely effected by this choice of scenario.

We find from the high-sensitivity observational estimate that in September about 4.1×10^6 km^2 of sea ice area are lost for each degree of global warming. In contrast, the low-sensitivity observational estimate gives about 3.3×10^6 km^2 of September sea ice loss per degree of global warming.

To examine the possible impact of internal variability on these estimates, we calculate the standard deviation of the 100 individual sensitivities we obtain from the bias-corrected Grand Ensemble for the period 1953–2016. These 100 individual sensitivities show a standard deviation of 0.3×10^6 km^2/°C, which is why we estimate a 95% likelihood range for the high-sensitivity observational estimate of September Arctic sea ice of $4.1 \pm 0.6 \times 10^6$ km^2 sea ice area loss per degree of global warming. This uncertainty arising from internal variability does not cover the observational estimate of the low-sensitivity observational estimate, implying that currently observational uncertainty and not internal variability dominates the uncertainty range when estimating the true sensitivity of Arctic summer sea ice. This statement is very likely true for the entire range of internal variability displayed by CMIP5 models (Olonscheck & Notz, 2017).

To quantify the amount of warming that would cause the Arctic Ocean to become nearly ice free, we examine at which level of warming sea ice area drops below 1×10^6 km^2. For the high-sensitivity observational estimate, we find that sea ice area in September drops below this threshold for about 1.7°C global warming. Considering the ensemble spread in sensitivities, we obtain a 95% confidence interval of 1.5°C to 1.9°C for the global warming at which September Arctic sea ice vanishes. Again, this range does not cover the range of uncertainty arising from observational uncertainty: the low-sensitivity observational estimate suggests a global warming of around 2.3°C for an ice-free Arctic Ocean during summer, well outside the range of the high-sensitivity observational estimate. Note that all these values are a conservative estimate of the global warming at which the Arctic Ocean loses its sea ice during summer for the first time, because we consider only monthly means.

Rosenblum and Eisenman (2016) estimate that the Arctic Ocean loses its summer sea ice once global warming rises above 1°C relative to the period 1980–1999. This translates to a global warming of about 1.8°C relative to preindustrial levels. Screen and Williamson (2017) conclude that the 2°C global warming target *might* be "insufficient to prevent an ice-free Arctic." Both these estimates lie within the range of observational uncertainty that we have identified here.

In March, when the sea ice coverage reaches its maximum, both observational estimates suggest a loss of about $1.6 \pm 0.3 \times 10^6$ km^2 of Arctic sea ice area for each degree of global warming. If this sensitivity were to remain unchanged in the future, the Arctic Ocean would become ice free all year round for a warming of about 9 ± 1.5°C. However, it is likely that the Arctic Ocean in reality becomes ice free all year round at lower levels of global warming. This is because in model simulations, with the thinning of the winter sea ice cover the linear relationship between winter sea ice coverage and global warming breaks down for higher amounts of global warming, giving eventually rise to a larger loss of winter sea ice per degree of global warming than currently observed (Bathiany et al., 2016; Li et al., 2013; Wagner & Eisenman, 2015).

To examine the seasonal cycle for a given amount of global warming in more detail, we obtain for each month the estimated sea ice area for specific amounts of global warming in our bias-corrected ensemble simulations (Figures 3 and S2). The resulting seasonal cycle for +1°C of global warming is very similar to the observed seasonal cycle of the past decade in the high-sensitivity observational estimate (black circles in Figure 3), as current global warming in the HadCRUT data set hovers at around +1°C relative to preindustrial levels.

We find that a warming of 1.5°C relative to preindustrial levels causes for the high-sensitivity observational estimate on average a reduction of Arctic summer sea ice to about 20% of presatellite sea ice area. In absolute terms, average September sea ice area for this warming would be about 1.6×10^6 km^2, compared to a presatellite level of about 6.7×10^6 km^2. Internal variability causes a standard deviation of $\pm 0.47 \times 10^6$ km^2 around the mean value, giving a 12% chance of having a near-ice-free Arctic Ocean during September for a global-mean warming of 1.5°C. Again, observational uncertainty dominates the uncertainty estimate, as the low-sensitivity observations suggest instead a reduction of September sea ice to around 3.3×10^6 km^2

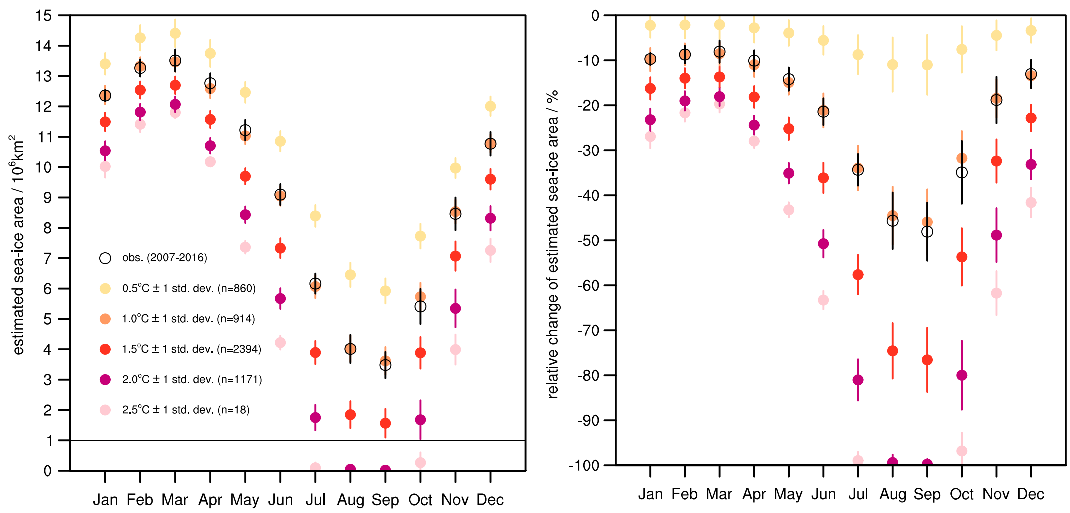

Figure 3. Annual cycle of estimated sea ice area for specific degrees of warming with respect to preindustrial, based on a bias correction toward the high-sensitivity observational record. The left panel shows absolute values, the right panel the relative change of sea ice area with respect to 1953–1978. Mean observed Arctic sea ice area for the period 2007–2016 is included as black circles. Mean global warming for this period is estimated to just below +1.0°C relative to preindustrial levels. The horizontal line marks the threshold of 1×10^6 km^2 that we take as a measure of a nearly ice-free Arctic. See Figure S2 for an equivalent figure based on the low-sensitivity observational record.

(Figure S2) for a warming of 1.5°C. This is about the sea ice coverage that the National Snow and Ice Data Center sea ice index shows for today.

For a warming of 2.0°C, the Arctic loses for the high-sensitivity observational estimate its summer sea ice throughout both August and September in all bias-corrected ensemble members. In July and October, estimated monthly mean sea ice area lies below 2×10^6 km^2, somewhat less than the amount of sea ice that was observed during the extreme minimum in September 2012, when Arctic sea ice area was about 2.6×10^6 km^2. Given the additional impact of internal variability, there is a 15% chance of having a near-ice-free Arctic Ocean for at least three consecutive months between July and October for a global-mean warming of 2.0°C if the high-sensitivity observational estimate was realistic.

In contrast, for the low-sensitivity observational estimate the Arctic Ocean very likely remains sea ice covered in all months for a warming of 2.0°C (Figure S2). In September, sea ice is reduced by about 80% to 1.6×10^6 km^2. Internal variability gives a standard deviation of $\pm 0.46 \times 10^6$ km^2 and thus only a 10% probability of having a near-ice-free Arctic Ocean for 2.0°C global warming.

In March, a global warming of 1.5°C causes a reduction of sea ice area to about 85% relative to presatellite values for both observational estimates. In absolute terms, sea ice area drops from a presatellite level of about 15×10^6 km^2 to about 13×10^6 km^2. For a warming of 2.0°C, March sea ice area is reduced to about 12×10^6 km^2, which is roughly 80% of the presatellite area.

If global warming were to rise above the levels aimed for in the Paris Agreement, sea ice would diminish further. For example, for a global warming of 2.5°C, the Arctic Ocean becomes ice free in all bias-corrected ensemble members from July to October for the high-sensitivity observational estimate and shows a reduction of sea ice area to below 1.6×10^6 km^2 for the months August and September based on the low-sensitivity observational estimate.

3.2. Spatial Distribution of Sea Ice

To estimate the impact of global warming and internal variability on the areal distribution of Arctic sea ice, we use our model simulations with corrected temperature biases, as described in section 2. We first identify in which years the bias-corrected ensemble members have a global-mean temperature of ± 0.05 around a given warming level. We then examine in how many of these years there is more than 15% sea ice coverage in any given grid cell. This allows us to construct maps of sea ice likelihood for a given amount of global warming (Figures 4 and S3).

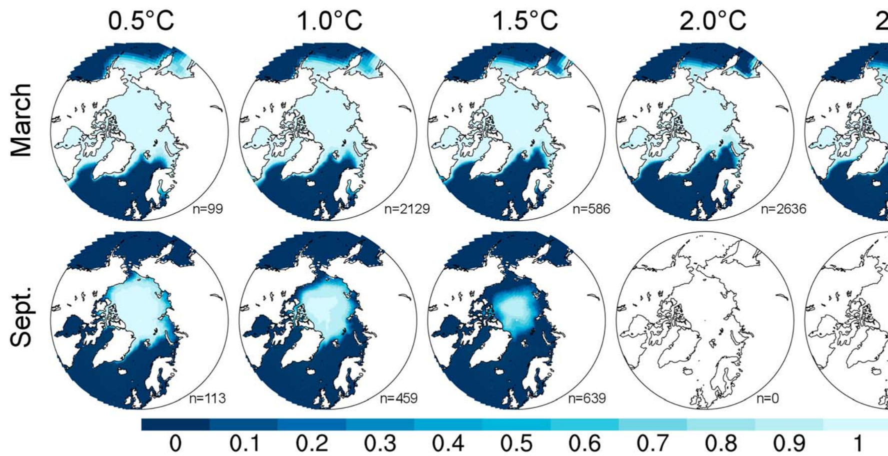

Figure 4. Likelihood of sea ice coverage for specific warming levels as estimated from the Max Planck Institute Grand Ensemble bias corrected toward the high-sensitivity observational estimate. For each warming level, we extracted all years from the simulations that have a global-mean temperature of ±0.05°C around that warming level. The figure shows for each warming level for March and September the fraction of these selected years that have a sea ice concentration of more than 15% in any given grid cell. The numbers in each panel indicate the number of years for which global warming levels were ±0.05°C around the given warming levels in all simulations of the Max Planck Institute Grand Ensemble. See the equivalent Figure S3 for the low-sensitivity observational estimate.

For present global warming levels of around +1.0°C compared to preindustrial levels, the likelihood of sea ice coverage from our ensemble simulation captures the observed reductions in summer sea ice in the Kara Sea, the Laptev Sea, and at the Alaskan coast (Serreze et al., 2007). This lends some credibility to the estimated areal patterns, in addition to the overall model evaluation provided by Notz et al. (2013). We should nevertheless note that uncertainty of these maps is substantially higher than the uncertainties of the overall reduction in sea ice area discussed before, as the reliability of the maps depends on the model's skill in reproducing the actual patterns of the sea ice loss.

For increasing global warming, we find that in March the simulated likelihood of sea ice coverage in any given grid cell only changes along the marginal ice zone. While the central Arctic Ocean remains ice covered in all years with a warming of +2.5°C above preindustrial levels, for this warming the likelihood of winter sea ice coverage is much reduced, for example, along the western and northern coasts of Svalbard and Novaja Semlija, in the Sea of Okhotsk, and in parts of the Kara Sea.

In September, at a warming of 1.5°C the simulated likelihood of sea ice coverage is substantially reduced for the high-sensitivity observational estimate along the Siberian and North American coasts. As discussed, at a warming of 2.0°C and more, the Arctic Ocean is ice free in September in our simulations for all ensemble members bias corrected toward the high-sensitivity observational estimate. For the low-sensitivity observational estimate, at 2.0°C global warming sea ice coverage is reduced along the coasts and looks similar to the spatial pattern at 1.5°C warming of the high-sensitivity observational estimate. Also, for a warming of 2.5°C there is some sea ice left in the Central Arctic Ocean and at the northern coast of Greenland and the Canadian archipelago (Figure S3). However, the uncertainty is large and the number of events for this global warming level is small.

4. Summary

In this contribution, we have combined the observed evolution of Arctic sea ice with simulations from the MPI-ESM Grand Ensemble, which consists of 100 simulations each under historical forcing, RCP2.6 forcing and RCP4.5 forcing. We have bias corrected the model simulations to match the observed Arctic sea ice loss per degree of global warming, using two different observational estimates of sea ice sensitivity. This approach has allowed us to estimate the simultaneous impact of external forcing, observational uncertainty, and internal variability on the evolution of the Arctic sea ice cover for limited amounts of global warming. Our results can be summarized as follows:

1. There is substantial observational uncertainty of Arctic sea ice sensitivity for a given degree of global warming. This uncertainty arises both from uncertainty in the estimate of the warming and from uncertainty in

the estimate of sea ice area. This observational uncertainty is dominating over additional uncertainty arising from internal variability.

2. The loss of Arctic sea ice per degree of global warming is largest in summer, with an observed decrease in sea ice area during July, August, and September of more than 4×10^6 km^2 per degree of global warming for the high-sensitivity observational estimate and of more than 3×10^6 km^2 per degree of global warming for the low-sensitivity observational estimate. The decrease of winter sea ice area per degree of global warming is about half as large.
3. If the high-sensitivity observational estimate of sea ice loss was realistic, the Arctic would become nearly ice free in September for a global warming of around 1.7°C relative to preindustrial levels. The Grand Ensemble suggests a 95% likelihood interval of around $\pm$0.2°C for this estimate. This suggests that the United Nations target of a maximum +1.5°C above preindustrial levels likely would allow Arctic sea ice to continue existing all year round, while a global warming of +2.0°C above preindustrial levels would cause the Arctic Ocean to become ice free throughout August and September. In contrast, the low-sensitivity observational estimate suggests that sea ice is on average only lost for a global warming of 2.2°C. This implies that September sea ice might still be around at +2.0°C global warming with a likelihood of 10%. These estimates cover the range of findings by Rosenblum and Eisenman (2016) and Screen and Williamson (2017).
4. In March, sea ice area is reduced to between 80 and 85% of presatellite sea ice area for a global warming between +1.5°C and +2.0°C relative to preindustrial levels. In particular, the ocean areas around Svalbard, Novaja Semlija, and in the Sea of Okhotsk could lose substantial amounts of their winter sea ice for these lower-end global warming targets.

By combining the observed sensitivity of Arctic sea ice with model estimates of internal variability, we find that most likely, the Arctic Ocean becomes ice free throughout September at a global warming of between 1.7°C and 2.2°C relative to preindustrial levels. Hence, the 1.5°C global warming target might only be marginally sufficient to prevent the near-complete loss of Arctic summer sea ice.

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References

Bathiany, S., Mauritzen, M., Raedel, G., & Brovkin, V. (2016). On the potential for abrupt arctic winter sea ice loss. *Journal of Climate*, *29*, 2703–2719. https://doi.org/10.1175/JCLI-D-15-0466.1

Bittner, M., Schmid, H., Timmreck, C., & Sienz, F. (2016). Using a large ensemble of simulations to assess the Northern Hemisphere stratospheric dynamical response to tropical volcanic eruptions and its uncertainty. *Geophysical Research Letters*, *43*, 9324–9332. https://doi.org/10.1002/2016GL070587

Cavalieri, D., & Parkinson, C. (2012). Arctic sea ice variability and trends, 1979–2010. *The Cryosphere*, *6*, 881–889. https://doi.org/10.5194/tc-6-881-2012

Fetterer, F., Knowles, K., Meier, W., Savoie, M., & Windnagel, A. (2016). *Sea ice index, version 2*. Boulder, CO: National Snow and Ice Data Center NSIDC. https://doi.org/10.7265/N5736NV7

Giorgetta, M. A., Jungclaus, J., Reick, C. H., Legutke, S., Bader, J., Böttinger, M., … Stevens, B. (2013). Climate and carbon cycle changes from 1850 to 2100 in MPI-ESM simulations for the Coupled Model Intercomparison Project phase. *Journal of Advances in Modeling Earth Systems*, *5*, 572–597. https://doi.org/10.1002/2016GL070587

Gregory, J., Stott, P., Cresswell, D., Rayner, N., Gordon, C., & Sexton, D. (2002). Recent and future changes in Arctic sea ice simulated by the HadCM3 AOGCM. *Geophysical Research Letters*, *28*, 2175. https://doi.org/10.1029/2001GL014575

Hansen, J., Ruedy, R., Sato, M., & Lo, K. (2010). Global surface temperature change. *Reviews of Geophysics*, *48*, RG4004. https://doi.org/10.1029/2010RG000345

Hedemann, C., Mauritsen, T., Jungclaus, J., & Marotzke, J. (2017). The subtle origins of surface-warming hiatus. *Nature Climate Change*, *7*, 336–339. https://doi.org/10.1038/nclimate3274

Jungclaus, J., Fischer, N., Haak, H., Lohmann, K., Marotzke, J., Matei, D., … von Storch, J.-S. (2013). Characteristics of the ocean simulations in MPIOM, the ocean component of the MPI Earth System Model. *Journal of Advances in Modeling Earth Systems*, *5*, 422–446. https://doi.org/10.1002/jame.20023

Li, C., Notz, D., Tietsche, S., & Marotzke, J. (2013). The transient versus the equilibrium response of sea ice to global warming. *Journal of Climate*, *26*, 5624–5636. https://doi.org/10.1175/JCLI-D-12-00492.1

Mahlstein, I., & Knutti, R. (2012). September Arctic sea ice predicted to disappear near 2°C global warming above present. *Journal of Geophysical Research*, *117*, D06104. https://doi.org/10.1029/2011JD016709

Meier, W., Stroeve, J., & Fetterer, F. (2007). Whither Arctic sea ice? A clear signal of decline regionally, seasonally and extending beyond the satellite record. *Annals of Glaciology*, *46*, 428–434. https://doi.org/10.3189/172756407782871170

Morice, C., Kennedy, J., Rayner, N., & Jones, P. (2012). Quantifying uncertainties in global and regional temperature change using an ensemble of observational estimates: The HadCRUT4 data set. *Journal of Geophysical Research*, *117*, D08101. https://doi.org/10.1029/2011JD017187

Notz, D. (2014). Sea-ice extent and its trend provide limited metrics of model performance. *The Cryosphere*, *8*, 229–243. https://doi.org/10.5194/tc-8-229-2014

Notz, D., & Marotzke, J. (2012). Observations reveal external driver for Arctic sea-ice retreat. *Geophysical Research Letters*, *39*, L08502. https://doi.org/10.1029/2012GL051094

Notz, D., & Stroeve, J. (2015). Insights on past and future sea-ice evolution from combining observations and models. *Global and Planetary Change*, *135*, 119–132. https://doi.org/10.1016/j.gloplacha.2015.10.011

Notz, D., & Stroeve, J. (2016). Observed Arctic sea-ice loss directly follows anthropogenic CO_2 emissions. *Science*, *354*, 747–750. https://doi.org/10.1126/science.aag2345

Notz, D., Haumann, A., Haak, H., Jungclaus, J., & Marotzke, J. (2013). Arctic sea-ice evolution as modeled by Max Planck Institute for Meteorology's Earth system model. *Journal of Advances in Modeling Earth Systems*, *5*, 173–194. https://doi.org/10.1002/jame.20016

Olonscheck, D., & Notz, D. (2017). Consistently estimating internal climate variability from climate model simulations. *Journal of Climate*, *30*, 9555–9573. https://doi.org/10.1175/JCLI-D-16-0428.1

Rayner, N. A., Parker, D. E., Horton, E. B., Folland, C. K., Alexander, L. V., Rowell, D. P., … Kaplan, A. (2003). Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *Journal of Geophysical Research*, *108*(D14), 4407. https://doi.org/10.1029/2002JD002670

Ridley, J., Lowe, J., & Hewitt, H. (2012). How reversible is sea ice loss? *Cryosphere*, *193*, 193–198. https://doi.org/10.5194/tc-6-193-2012

Rosenblum, E., & Eisenman, I. (2016). Faster arctic sea ice retreat in CMIP5 than in CMIP3 due to volcanoes. *Journal of Climate*, *29*, 9179–9188. https://doi.org/10.1175/JCLI-D-16-0391.1

Rosenblum, E., & Eisenman, I. (2017). Sea ice trends in climate models only accurate in runs with biased global warming. *Journal of Climate*, *30*, 6265–6278. https://doi.org/10.1175/JCLI-D-16-0455.1

Screen, J., & Williamson, D. (2017). Ice-free Arctic at 1.5°C? *Nature Climate Change*, *7*, 230–231. https://doi.org/10.1038/nclimate3248

Serreze, M., Holland, M., & Stroeve, J. (2007). Perspectives on the Arctic's shrinking sea-ice cover. *Science*, *325*(5818), 1533–6. https://doi.org/10.1126/science.1139426

Simmonds, I. (2015). Comparing and contrasting the behaviour of Arctic and Antarctic sea ice over the 35 year period 1979–2013. *Annals of Glaciology*, *56*(69), 18–28. https://doi.org/10.3189/2015AoG69A909

Stevens, B. (2015). Rethinking the lower bound on aerosol radiative forcing. *Journal of Climate*, *28*, 4794–4819. https://doi.org/10.1175/JCLI-D-14-00656.1

Stroeve, J., Kattsov, V., Barrett, A., Serreze, M., Pavlova, T., Holland, M., & Meier, W. (2012). Trends in Arctic sea ice extent from CMIP5, CMIP3 and observations. *Geophysical Research Letters*, *39*, L16502. https://doi.org/10.1029/2012GL052676

Suárez-Gutiérrez, L., Li, C., Thorne, P., & Marotzke, J. (2017). Internal variability in simulated and observed tropical tropospheric temperature trends. *Geophysical Research Letters*, *44*, 5709–5719. https://doi.org/10.1002/2017GL073798

Taylor, K., Stouffer, R., & Meehl, G. (2012). An overview of CMIP5 and the experiment design. *Bulletin of the American Meteorological Society*, *93*, 485–498. https://doi.org/10.1175/BAMS-D-11-00094.1

Titchner, H. A., & Rayner, N. A. (2014). The Met Office Hadley Centre sea ice and sea surface temperature data set, version 2: 1. Sea ice concentrations. *Journal of Geophysical Research: Atmospheres*, *119*, 2864–2889. https://doi.org/10.1002/2013JD020316

United Nations Framework Convention on Climate Change (2015). Paris Agreement, *United Nations, New York, No. 54113*. Retrieved from https://treaties.un.org/doc/Publication/UNTS/No%20Volume/54113/Part/I-54113-0800000280458f37.pdf

Wagner, T., & Eisenman, I. (2015). How climate model complexity influences sea ice stability. *Journal of Climate*, *28*, 3998–4014. https://doi.org/10.1175/JCLI-D-14-00654.1

Winton, M. (2011). Do climate models underestimate the sensitivity of northern hemisphere sea ice cover? *Journal of Climate*, *24*, 3924–3934. https://doi.org/10.1175/2011JCLI4146.1