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September sea-ice cover in the Arctic Ocean projected to vanish by 2100

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The Arctic climate is changing rapidly[1]. From 1979 to 2006, September sea-ice extent decreased by almost 25% or about 100,000 km^2 per year (ref. 2). In September 2007, Arctic sea-ice extent reached its lowest level since satellite observations began[3] and in September 2008, sea-ice cover was still low. This development has raised concerns that the Arctic Ocean could be ice-free in late summer in only a few decades, with important economic and geopolitical implications. Unfortunately, most current climate models underestimate significantly the observed trend in Arctic sea-ice decline[4], leading to doubts regarding their projections for the timing of ice-free conditions. Here we analyse the simulated trends in past sea-ice cover in 18 state-of-art-climate models and find a direct relationship between the simulated evolution of September sea-ice cover over the twenty-first century and the magnitude of past trends in sea-ice cover. Using this relationship together with observed trends, we project the evolution of September sea-ice cover over the twenty-first century. We find that under a scenario with medium future greenhouse-gas emissions, the Arctic Ocean will probably be ice-free in September before the end of the twenty-first century.

Climate models underestimate the decrease in September sea-ice extent (SSIE) during the 1979–2007 period, many to a large degree (Fig. 1). Moreover, the spread in the projected evolution of SSIE over the coming decades (also shown in Fig. 1) is huge. Whereas some models simulate nearly ice-free conditions in the 2070s, more than half the initial sea-ice cover remains by 2080–2099 in 7 out of the 18 models. From Fig. 1, it seems that the models with the most realistic SSIE trends in the 1979–2007 period are also the ones simulating early ice-free conditions in the Arctic. Figure 2 (solid line) confirms that evolution of SSIE during the twenty-first century is strongly linked to the magnitude of present-day trends in climate models. The correlation between future SSIE changes and present-day SSIE trends is consistently high: 0.90 at the beginning of the twenty-first century and 0.75 at the end.

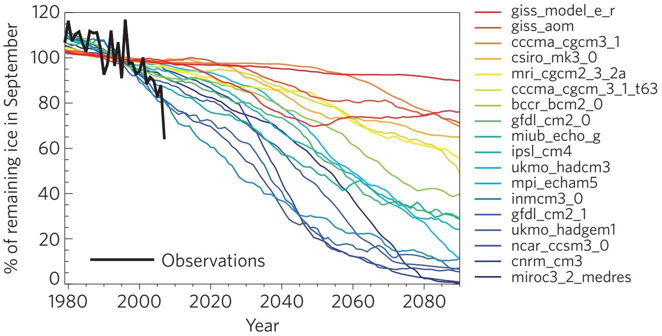

Figure 1 | Observed and simulated evolution of SSIE in the Arctic. The percentage of remaining sea-ice cover in September, as observed (black line) and simulated (coloured lines) by 18 climate models from the CMIP3 project[13], plotted as a function of time. The reference sea-ice extent is taken as the mean over the 1979–2007 period. Model values have been smoothed using a 20-year running average. The models are forced by the SRESA1B scenario after 2000 and by observed forcing during the twentieth century. Sea-ice extent observations used in this letter come from satellite passive microwave measurements[14]. Sea-ice extent is defined as the sum of the area of grid cells with at least 15% ice concentration.

The reason for this consistently high correlation is that simulated SSIE trends and future SSIE changes are both determined to a large extent by the baseline sea-ice thickness distribution. This parameter controls most of the intermodel variations in recent SSIE trends and continues to have an important role in SSIE evolution throughout the twenty-first century. Indeed, the percentage of total September ice cover constituted by ice that is 0.01–0.5 m thick in the 1950–1979 period is an excellent predictor of SSIE trends in the 1979–2007 period (anti-correlation of 0.75) and remains strongly anti-correlated with SSIE changes over the entire twenty-first century (Fig. 2, dashed line). Simple mechanisms can explain the strong relationship between fractional coverage of thin ice and transient ice loss. Areas of thin ice are expected to disappear faster, because to achieve the same loss of ice covered area, a smaller volume of ice must be melted, and thus less energy is needed. In addition, areas of thin ice have a greater susceptibility to albedo feedback[5]. The relationship between recent SSIE trends and future SSIE changes is therefore a physically credible one.

We can exploit this relationship and the fact that we have an observation of the recent trend to constrain future changes. Figure 3a illustrates the procedure. Each point corresponds to a Coupled Model Intercomparison Project phase 3 (CMIP3) model. We compute the regression line between current SSIE trends and the mean percentage of remaining sea-ice cover in the 2021–2040 period. The two quantities are clearly tightly linked, consistent with the high correlations of Fig. 2. (A small part of the discrepancy between the two quantities might be related to the fact that the models do not use exactly the same forcing during the twentieth century[6].) Our estimate of SSIE change in the 2021–2040 period is then the intercept between the regression line and the vertical line indicating the observed current trend. A confidence interval associated with this predicted value can be estimated on the basis of the linear regression model.

The same operation is repeated for each 20-year segment between 2005–2099. Figure 3b shows the resulting estimate of the evolution of SSIE with the associated 68% confidence interval range.

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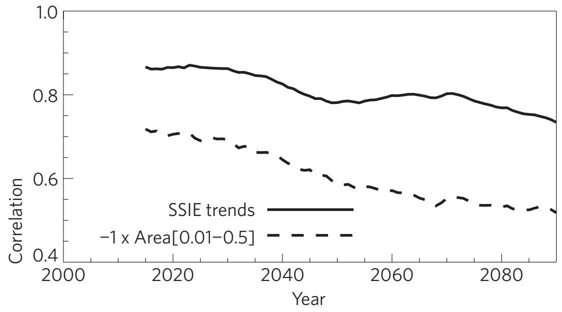

Figure 2 | Relationship between SSIE changes through the twenty-first century in the CMIP3 models and historical sea-ice cover properties. Each point of the solid line represents the correlation between the mean percentage of remaining sea-ice cover in September computed on a centred 20-year window and the simulated SSIE trends in the 1979–2007 period. Each point of the dashed line represents the correlation between the mean percentage of remaining sea-ice cover in September computed over a centred 20-year window and Area[0.01–0.5] (multiplied by −1), where Area[0.01–0.5] is the percentage of total September ice cover constituted by ice that is 0.01–0.5 m thick in the 1950–1979 period.

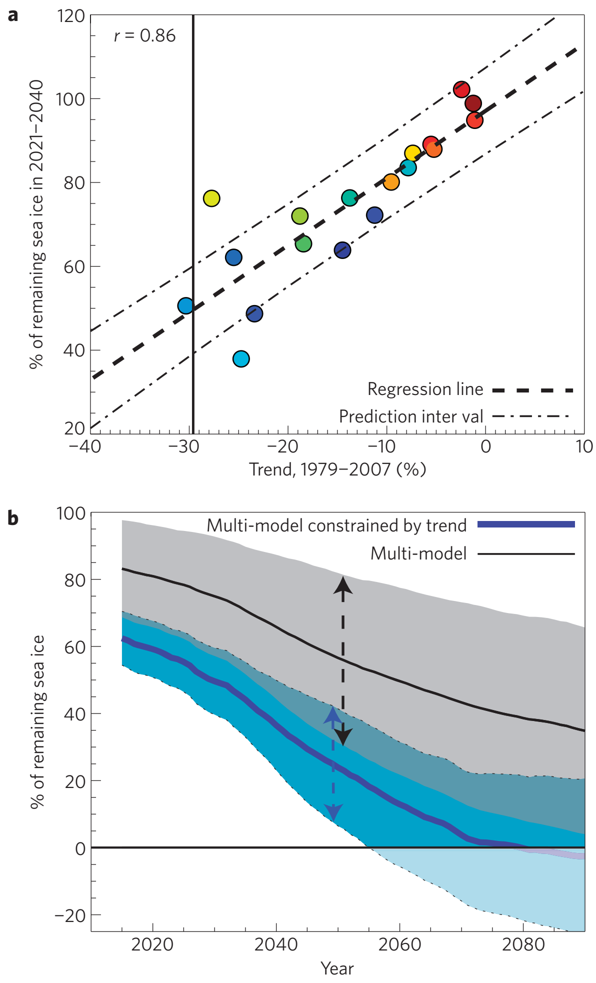

Figure 3 | Illustration of the methodology developed to project future SSIE changes and projected future SSIE changes. a, Mean simulated percentage of remaining sea ice in September in the 2021–2040 period as a function of the trend in the 1979–2007 period. Each point corresponds to a CMIP3 model; colours match those of Fig. 1. The vertical bar denotes the observed trend. The 68% confidence prediction interval is estimated using the linear regression model. **b**, Projected evolution of remaining sea-ice cover in September over 20-year periods during the twenty-first century on the basis of our approach (dark blue line) and using the conventional approach of a multi-model average (black line). The associated 68% confidence intervals are also shown (clear blue for our approach and grey for the conventional approach, estimated as one inter-model standard deviation).

The simple multi-model averages for each 20-year segment are also shown. There are major differences between the ensemble mean and our estimate, increasing with time. The models as an ensemble systematically underestimate the sea-ice loss over the twenty-first century. Our estimate of the first 20-year period with climatological ice-free conditions in September in the Arctic is 2066–2085. This is slightly earlier than predicted, even by the models with the largest decreasing trends in the 1979–2007 period (see Fig. 1). The uncertainty interval derived with our approach increases with time, consistent with the weakening of the correlation between recent SSIE trends and future SSIE changes. However, it remains much smaller than the equivalent uncertainty range estimated using the conventional approach of simply measuring the spread in the model ensemble. On the basis of our approach, there is a probability of 16% that at least 20% of the baseline sea-ice cover in September remains at the end of the twenty-first century and the same probability that the ice disappears completely by 2046–2065. Note that these simulations are all based on the Special Report on Emissions scenario A1B (SRESA1B). If greenhouse-gas emissions increase at a greater rate than projected by the SRESA1B scenario, as is the case at present, at least with carbon dioxide[7], our prediction would be too conservative.

Figure 4 shows the results of a test of the sensitivity of our SSIE projection to the value of the observed trend, which has a crucial role in our methodology. Using the 1979–2006 trend instead of the 1979–2007 one, the ice cover does not totally disappear before the end of the twenty-first century. When the 1979–2008 trend is used, ice is likely to disappear as soon as 2059–2078. Therefore, including information about the loss of recent years does lead to earlier prediction of an ice-free Arctic. We also tested the sensitivity to the models used in the analysis. As shown in Fig. 4 our results do not depend crucially on the inclusion or exclusion of particular models. The estimate of SSIE change on the basis of our methodology is very similar to the value given by the model with the most realistic present-day trend (see Fig. 1). However, this need not be the case. On the basis of Fig. 4, removing this model or others with relatively realistic present-day trends from the analysis hardly changes our estimate.

The fact that current climate models are not able to perfectly reproduce observed SSIE trends does not mean useful information concerning the future evolution of sea ice cannot be derived from them. Indeed, our study illustrates a new way to improve climate change projections[8–10]. Even if none of the models is correct in its simulation of SSIE trends (or to generalize, current climate parameter) and of future SSIE changes (future climate parameter), together the models describe a systematic relationship between current and future climate parameters. The relationship can be used to make a prediction about the true value of the future climate parameters and the associated confidence interval, given a perfect observation of the current climate parameters. In this approach, there is a risk that the relationship between future and present climate parameters is an artefact of climate models. As we discussed above, we show that the relationship in our case is physically credible. However, it is still theoretically possible that some crucial processes are missing in all the models and that the relationship is not reliable: for example, as the representation of sea-ice processes in climate models is still generally rather crude, one could imagine that missing processes might lead either to a rapid

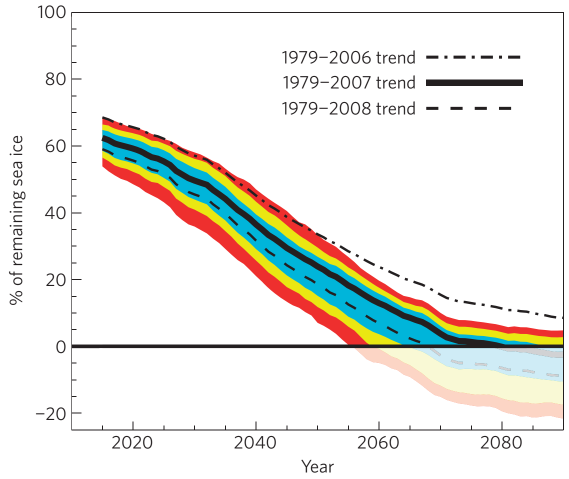

Figure 4 | Results of two sensitivity analyses of the projected SSIE. The black lines show the sensitivity to the value of the observed trend: the analysis of Fig. 3b, on the basis of the trend on the 1979–2007 period (−10.2% per decade) has been repeated using the trend calculated for the 1979–2006 period (−8.6% per decade) and the 1979–2008 period (−11.1% per decade). The colour shading shows the sensitivity to the models included in the analysis. The analysis of Fig. 3b (dark solid blue line) is repeated for all of the possible combinations of 15 (red shading), 16 (yellow shading), 17 (blue shading) models among the 18 models. The shading represents the range of the response obtained in the three cases.

nonlinear reduction in sea-ice or stabilize sea-ice cover. Such missing processes would of course also compromise a conventional ensemble mean projection.

The current approach to reducing the spread of climate change projections implicitly relies on the increasing realism of climate models: as the models become higher in resolution with fewer parameterized processes and/or better parameterizations, hopefully they will become more realistic and their projections of climate change will converge. However, the convergence may be too slow and difficult[11] and complementary approaches are needed. Alternatively, an ensemble of models may be used to trace out physically credible relationships between future climate change and verifiable aspects of the current climate. In this sense, the intermodel spread is actually useful and desirable as it allows a better sampling of the relationship between current and future climate parameters. Generating inter-model spread in a systematic way to represent adequately the full range of underlying uncertainties in physical parameterizations as in the 'perturbed physics approach'[12] may be a valuable methodology for this purpose. 'All models are wrong, some are useful' said the famous statistician George Box. We would add that many models—each wrong in a different way—can collectively be as useful as a nearly perfect one, as long as observations exist to guide interpretations of their predictions.

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Author contributions

A.H., J.B. and X.Q. are responsible for project planning. J.B. carried out most of the analysis. J.B. and A.H. wrote the paper. All of the authors contributed to discussions of the results and commented on the manuscript.

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