Ice-free at 1.5°C?

James A. Screen[1] and Daniel Williamson[1]

[1]*Department of Mathematics, University of Exeter, Exeter, EX4 4QE, UK*

To the Editor − The Paris Agreement[1] to combat climate change includes an aspirational goal to limit global warming to 1.5°C above the pre-industrial level, substantially more ambitious than the previous target of 2°C. One of the most visible and iconic aspects of recent climate change is the dramatic loss of Arctic sea-ice[2], which is having profound implications on the environment, ecosystems and human inhabitants of this region and beyond[3].

The concept of an 'ice-free Arctic' has captured scientific attention[4-9] and public imagination. Scientists commonly define this as when the Arctic first becomes ice-free at the end of summer; specifically, the first year when the average September sea-ice extent falls below 1 million km^2. This threshold is considered appropriate, rather than zero, because some land-fast ice is expected to remain along the northern coasts of Greenland and Ellesmere Island for many years after the bulk of the Arctic Ocean first becomes open water[4]. Without efforts to slow manmade global warming, an ice-free Arctic would likely occur in summer by the middle of this century[2,4-9]. But would limiting warming to 1.5°C, or even 2°C, prevent the Arctic ever going ice-free?

Different climate models give vastly different projections of the lowest sea-ice extent for global warming of less than 1.5°C (**Fig. 1a**) or less than 2°C (**Fig. 1b**). Models that over-estimate (or under-estimate) sea-ice extent in the last ten years are also those that project more ice (or less ice) remaining into the future. This can be summarised mathematically by the strong log-linear relationship (we use logarithms because sea-ice extent cannot physically be less than zero) between model-simulated sea-ice extent averaged for years 2007 to 2016 and the minimum sea-ice extent for global warming of up to 1.5°C (**Fig. 1a**) or up to 2°C (**Fig. 1b**). Using the observed sea-ice extent for the last decade (4.8 million km^2) as a predictor in our simple regression models yields an observationally-constrained prediction of 2.9 million km^2 (90% credible interval: 2.5 to 3.4 million km^2) for the minimum sea-ice extent if global warming is limited to 1.5°C (**Fig. 1a**), or 1.2 (0.4 to 4.0) million km^2 if global warming remains below 2°C (**Fig. 1b**).

Using Bayesian statistics allows us to compare estimates of the probability of an ice-free Arctic for the 1.5°C or 2°C target (**Fig. 1c**). We estimate there is less than a 1-in-100000 (*exceptionally unlikely* in IPCC parlance[2]) chance of an ice-free Arctic if global warming stays below 1.5 °C, and around a 1-in-3 chance (39%; *about as likely as not*) if global warming is limited to 2.0°C. We suppose then that a summer ice-free Arctic is *virtually certain* to be avoided if the 1.5°C target of the Paris Agreement is met. However, the 2°C target may be insufficient to prevent an ice-free Arctic. Furthermore, our analysis suggests that the Intended Nationally Determined Contributions submitted by countries to support the Paris Agreement (which imply warming of around 3°C[10]) would *likely* (73%) lead to the Arctic becoming ice-free (**Fig. 1c**).

1. UNFCCC. http://unfccc.int/paris_agreement/items/9485.php (2015)
2. IPCC. *Climate Change 2013: The Physical Science Basis* (2013)
3. Cohen, J. *et al. Nature Geosci.* **7**, 627-637 (2014)
4. Wang, M. & Overland, J. E. *Geophys. Res. Lett.* **36**, L07502 (2009)
5. Boe, J., Hall, A. & Qu, X. *Nature Geosci.* **2**, 341–343 (2009)

6. Liu, J., Song, M., Horton, R. M. & Hu, Y. *Proc. Natl. Acad. Sci. USA* **110**, 12571–12576 (2013)
7. Massonnet, F., *et al*. *Cryosphere* **6**, 1383–1394 (2012)
8. Mahlstein, I. & Knutti, R. *J. Geophys. Res.* **117**, D06104 (2012)
9. Notz, D. & Stroeve, J. *Science* **354**, 747-750 (2016)
10. Rogelj, J., *et al*. *Nature* **534**, 631-639 (2016)

Acknowledgements

The authors are grateful to the climate modeling groups for producing and making available their model output and to the following data providers: National Snow and Ice Data Center (observed sea-ice extent) and Earth System Grid (CMIP5 multi-model ensemble).

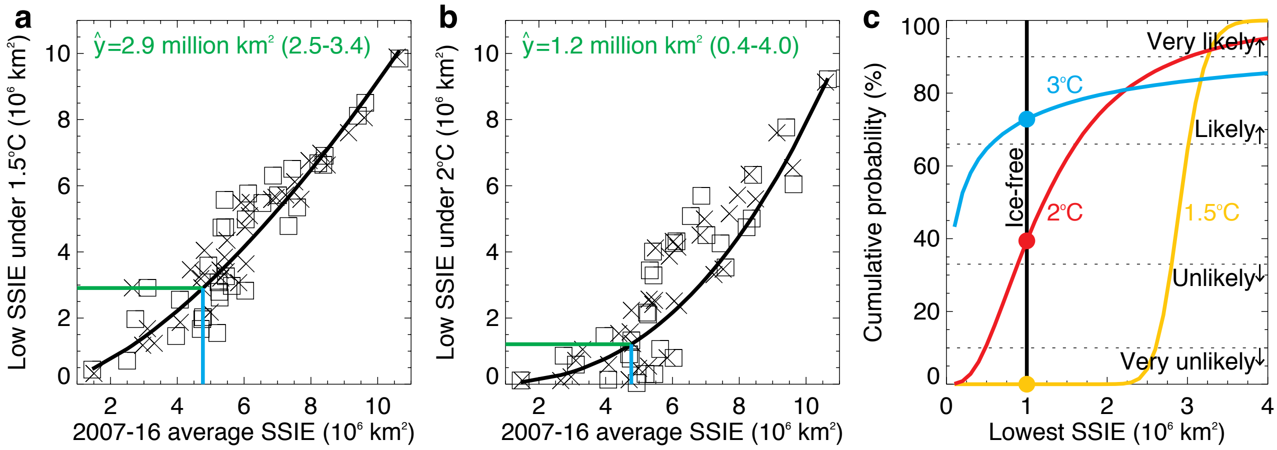

Figure 1. Predicting the likelihood of an ice-free Arctic for the 1.5°C and 2°C targets. **a**, Model projections of the minimum September-mean sea-ice extent (SSIE) for global warming of less than 1.5°C plotted against the 2007-2016 average SSIE. Each symbol corresponds to output from a different CMIP5 model forced by historical emissions from 1850 to 2005 and then either a strong (RCP8.5; crosses) or medium (RCP4.5; squares) greenhouse gas emissions scenario through to 2100. In each case we identified the first year when the annual- and global-mean surface temperature exceeded 1.5°C above the pre-industrial level (1862-1900) and found the lowest (non-zero) SSIE prior to that year. Simulations that do not reach 1.5°C by 2100 are excluded from the analysis. For reference, in the analysed simulations the average year of exceeding 1.5°C is 2026 and 2°C is 2043. The black line shows the log-linear regression model. To ensure positive predictions, we take the natural logarithm of SSIE and fit a standard Bayesian linear regression (with reference prior distributions so that the fit coincides with that obtained by ordinary least squares). The observed 2007-2016 average SSIE (blue) is used as a predictor in the regression model to provide an observationally-constrained prediction $\hat{y}$ (green) of the minimum SSIE for global warming below 1.5°C. **b**, As **a** but for projections of the minimum SSIE for global warming of less than 2°C. **c**, Cumulative probability distribution of $\hat{y}$ for global warming below 1.5°C (yellow), below 2°C (red) and below 3°C (blue) obtained by Monte Carlo sampling (n=100000) from the posterior predictive

distribution for $\hat{y}$. The 1 million km^2 SSIE threshold and IPCC likelihood ranges are indicated.