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Response of winter climate and extreme weather to projected Arctic sea-ice loss in very large-ensemble climate model simulations

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Arctic sea-ice loss and amplified Arctic warming have been one striking signature of climate change, which have important impacts on climate variability in the Arctic and mid-low latitudes. Climate modeling including the Polar Amplification Model Intercomparison Project (PAMIP) has been a powerful tool for investigating the effects of Arctic sea-ice loss in a changing climate. However, existing climate model simulations including individual climate models from the multi-model/ensemble PAMIP project have relatively small ensemble sizes that may not allow a robust separation of forced response, particularly the response of extremes, to Arctic sea-ice loss from internal variability. Therefore, our confidence in the response to projected Arctic sea-ice loss in climate change is reduced. This has led to two unanswered important questions: (1) what ensemble sizes are needed for robust detection of extremes, as well as seasonal-mean responses to projected Arctic sea-ice loss? and (2) is the response dependent on resolution?

To address the challenge, we have performed very large (~2000 members) initial-condition ensemble climate simulations, using both low (~90 km) and high (~60 km) resolutions, with prescribed boundary conditions (i.e., sea surface temperature and sea-ice concentration) taken from the PAMIP project, to advance understanding of mean climate and extreme weather responses to projected Arctic sea-ice loss under 2°C global warming above preindustrial levels. We have run these simulations with the Met Office Hadley Centre global atmospheric model Version 4 on the University of Oxford's innovative distributed computing project (Climateprediction.net). These simulations better sample internal atmospheric variability and extremes for each model compared to those from the PAMIP, and also allow studying the resolution-dependence of the response to projected Arctic sea-ice using a larger ensemble. Analysis of these simulations suggests that the mean climate response is mostly consistent with that from the PAMIP multi-model ensemble, including tropospheric warming, reduced midlatitude westerlies and storm track activity, an equatorward shift of the eddy-driven jet and increased mid-to-high latitude blocking. The response of temperature and precipitation extremes largely follows the seasonal-mean response. However, East Asia is a notable exception in showing an increase in severe cold temperature extremes in response to the projected Arctic sea-ice loss. Two resolutions of the

same model exhibit significant differences in the stratospheric circulation. This does suggest resolution-dependence of the response but we consider that the difference in the stratospheric response weakly modulates the tropospheric response.

We highlight that our very large-ensemble simulations have allowed rigorous sub-sampling to address the challenge of obtaining a robust forced response to projected Arctic sea-ice loss. The sub-sampling confirms that large ensembles (e.g. >=400) are needed to robustly estimate the seasonal-mean large-scale circulation response, and very large ensembles (e.g., >=1000) for regional climate and extremes. The reduction in uncertainty of the response with ensemble size is very well predicted by standard error analysis, guiding the design of future large ensembles.