



## How large does a large ensemble need to be?

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Future observed climate will be a combination of the forced change due to anthropogenic greenhouse gas emissions and internal climate variability. With a limited number of ensemble members of a climate model it is difficult to distinguish between the forced response of the system to external forcing and internal variability. This can lead to public confusion, such as that around the recent “hiatus” or “slowdown in global warming”, which indeed has been attributed to internal variability of the climate system.

Previous studies have investigated the required ensemble size for individual quantities using the 100-member Max Planck Institute Grand Ensemble (MPI-GE). For example, Maher et al (2018) find that 30-40 ensemble members are needed to robustly estimate El Niño Southern Oscillation (ENSO) variability, although less could be used if a larger error is acceptable. Conversely, Olonscheck Notz (2017) use the ensemble simulations of the Coupled Model Intercomparison Project 5 (CMIP5) and MPI-GE to suggest that multiple small ensembles of coupled climate models are of more use than either a large ensemble or a multi-model ensemble with single realizations. These results clearly demonstrate that the required number of ensemble members depends on both the quantity and the level of accuracy that is deemed sufficient.

This study provides a broadly applicable methodology to estimate the required ensemble size for any given quantity. We use both the control simulations and ensemble simulations from CMIP5 and MPI-GE to provide an estimate of the required ensemble size for investigating the forced response and internal variability for characteristic quantities of the climate system such as global-mean surface air temperature, the Atlantic Meridional Overturning Circulation, and regional precipitation. We also discuss how averaging over time can be used to compensate for smaller ensemble sizes, when internal variability does not change over time and large ensembles are not available. The methodology presented in this study will inform modeling centers and future studies as to how large an ensemble should ideally be.