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Statistical methods for estimating the forced component of historical SST and precipitation changes: A bias-variance tradeoff

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Distinguishing the influences of externally forced responses and internal variability on the observed climate is critical for attributing historical climate change and for evaluating the forced responses simulated by climate models. Statistical methods such as optimal fingerprinting, low-frequency component analysis (LFCA), and dynamical adjustment have proven useful for this application. The skill of such statistical methods can be evaluated using climate model large ensembles, where the forced response is estimated by averaging over many realizations. Our study uses large ensemble simulations from five different climate models to evaluate the performance of three statistical methods for this application: (1) low-frequency component analysis, (2) signal-to-noise maximizing pattern optimal fingerprinting (SNMP-OF), which uses the patterns from an ensemble-based signal-to-noise maximizing pattern (SNMP) analysis for optimal fingerprinting, and (3) a novel method based on SNMP analysis called fingerprint maximizing patterns (FMP), which finds patterns within observed variability that have the maximum fingerprint of the model-based forced response.

We investigate how the root mean square error (RMSE) of these three methods varies across the choices of hyperparameters and show that all methods have a similar maximum skill. However, the contribution to the RMSE from the mean bias in the forced response estimate varies across the methods, with SNMP-OF and FMP showing a larger mean bias than LFCA. This demonstrates that methods that largely rely on the model forced response to obtain the observed forced response may give biased estimates and underestimate the uncertainty in these estimates due to the bias-variance tradeoff.

Additionally, we apply these methods to observed Sahel precipitation, which is extensively debated in terms of its forced component, and closely related North Atlantic sea surface temperatures (SSTs). We show that while the methods give a robust estimate of the forced response in North Atlantic SSTs from 1950 to 2022, their estimates of the forced response in Sahel precipitation over the same period differ in sign. The fact that these estimates of the Sahel precipitation response differ substantially, despite all methods performing similarly well for large ensembles, suggests substantial epistemic uncertainty in estimates of the forced precipitation response in this region.