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Exploring Kalman methods for parameter estimation in coupled climate models at multidecadal scales

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In past climate reanalyses for multi-decadal or longer scales with coupled Global Circulation models (GCMs), it can be assumed that the growth of prediction errors mainly arises from imprecisely known model parameters, which have a nonlinear relationship with the climate proxy observations. High-resolution coupled GCMs for climate analysis are extremely expensive to run, which constrains the applicability of existing assimilation approaches. In a model framework were we assume that model dynamic parameters account for all forecast errors at observation times, we compare two low-cost iterative schemes for approximate nonlinear model parameter estimation, and its physically consistent state. First, a trivial adaptation of the strong constraint incremental 4D-Var formulation leads to what we refer to as the parameter space iterative extended Kalman smoother (pIKS), a Gauss-Newton scheme. Second, a so-called parameter space fractional Kalman smoother (pFKS) is an alternative controlled-step line search, which can potentially be a more stable approach. While these iterative schemes are known and have been used in data assimilation, we revisit them within the context of parameter estimation in climate reanalysis, as compared to the more general 4D-Var formulation for Numerical Weather Prediction (NWP). Then, the two schemes are evaluated in numerical tests with a simple 1D energy Balance Model and with a fully-coupled Community Earth System Model (CESM v1.2), whose application to multi-decadal past climate reanalysis is the motivation for this study. The two schemes show advantages over the ensemble transform Kalman filter (ETKF).