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Linear and nonlinear response to parameter variations in a mesoscale model

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It is widely recognized that ensemble prediction system (EPS) skill can improve when considering model error in the system design. Typical approaches include varying physical parameterization schemes or entire modeling systems within an EPS, and including stochastic terms in the dynamical equations. But perhaps the simplest approach to accounting for uncertainty in a model is to perturb inherently uncertain parameters within sub-grid parameterization schemes. Although it almost certainly cannot introduce all the modes of variability produced by other methods, its simplicity alone suggests that its effect on prediction skill and variability deserves quantitative scrutiny. In this work we seek to understand how perturbations to uncertain parameters manifest in a mesoscale model, and evaluate the potential for use in EPSs or data assimilation systems that can exploit ensemble covariances and linear or nonlinear responses.

A set of four parameters are varied, corresponding to one each in cumulus, cloud microphysics, boundary-layer turbulence, and radiation schemes within the Weather Research and Forecast (WRF) mesoscale numerical weather prediction model. Parameters are drawn only once from distributions intended to capture the uncertainty estimated by experts and reported in the literature. Each set of parameters is drawn with a Latin Hypercube Sampling technique that ensures the parameter sets are independent and fill the four-dimensional space spanned by the parameters. The parameter sets are then fixed and an ensemble of 10 members uses them for approximately 30 ensemble forecasts that are also subject to initial-condition, lateral boundary-condition and land-surface uncertainty.

We show that the parameters and state variables have clear linear relationship in certain regions and at certain times; elsewhere there may be either little dependence of the state on the parameter, or a nonlinear dependence. Linear response and ensemble sensitivity are quantified with simple lagged-regression techniques. Only one of the parameters that are perturbed leads to noticeable changes in model bias. The response to each parameter is different in magnitude and direction in the model state space; it does not simply follow a common sensitivity pattern. We deduce a nonlinear response from lack of measurable linear sensitivity and also by noting departures from statistical normality in the response.

We argue that a linear relationship between parameters and predictions is potentially useful for parameter estimation via data assimilation. The fact that this linear relationship varies in space and time suggests that the parameters themselves should be spatially and temporally varying. Parameters can then be treated as unobserved variables with spatial and temporal scales inferred from the scales of variation of the parameter-state relationships. One implication for ensemble data assimilation, for example, is that the number of ensemble members may need to be large, or some form of localization may need to be imposed, to effectively estimate parameters.