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Emulation for probabilistic weather forecasting

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Numerical weather prediction models are typically very expensive to run due to their complexity and resolution. Characterising the sensitivity of the model to its initial condition and/or to its parameters requires numerous runs of the model, which is impractical for all but the simplest models. To produce probabilistic forecasts requires knowledge of the distribution of the model outputs, given the distribution over the inputs, where the inputs include the initial conditions, boundary conditions and model parameters. Such uncertainty analysis for complex weather prediction models seems a long way off, given current computing power, with ensembles providing only a partial answer.

One possible way forward that we develop in this work is the use of statistical emulators. Emulators provide an efficient statistical approximation to the model (or simulator) while quantifying the uncertainty introduced. In the emulator framework, a Gaussian process is fitted to the simulator response as a function of the simulator inputs using some training data. The emulator is essentially an interpolator of the simulator output and the response in unobserved areas is dictated by the choice of covariance structure and parameters in the Gaussian process. Suitable parameters are inferred from the data in a maximum likelihood, or Bayesian framework. Once trained, the emulator allows operations such as sensitivity analysis or uncertainty analysis to be performed at a much lower computational cost.

The efficiency of emulators can be further improved by exploiting the redundancy in the simulator output through appropriate dimension reduction techniques. We demonstrate this using both Principal Component Analysis on the model output and a new reduced-rank emulator in which an optimal linear projection operator is estimated jointly with other parameters, in the context of simple low order models, such as the Lorenz 40D system. We present the application of emulators to probabilistic weather forecasting, where the construction of the emulator training set replaces the traditional ensemble model runs. Thus the actual forecast distributions are computed using the emulator conditioned on the ‘ensemble runs’ which are chosen to explore the plausible input space using relatively crude experimental design methods. One benefit here is that the ensemble does not need to be a sample from the true distribution of the input space, rather it should cover that input space in some sense. The probabilistic forecasts are computed using Monte Carlo methods sampling from the input distribution and using the emulator to produce the output distribution.

Finally we discuss the limitations of this approach and briefly mention how we might use similar methods to learn the model error within a framework that incorporates a data assimilation like aspect, using emulators and learning complex model error representations. We suggest future directions for research in the area that will be necessary to apply the method to more realistic numerical weather prediction models.