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Conditioning of the Weak-Constraint 4D-Variational Data Assimilation Problem

Nancy Nichols, Adam El-Said, and Amos Lawless
University of Reading, School of Mathematical and Physical Sciences, United Kingdom (n.k.nichols@reading.ac.uk)

Four-dimensional data assimilation (4DVar) has become a standard method in use by major operational weather forecasting centres. The aim of the method is to determine the most likely state of a dynamical system given observations of the system. Under certain statistical assumptions, the maximum a posteriori likelihood Bayesian estimate is obtained as the solution to a weighted nonlinear least squares problem subject to the model equations as strong constraints.

The model equations do not provide a perfect representation of the real dynamical system, however, and methods to allow for ‘model errors’ in the assimilation are a goal of current research. The aim is now to find an optimal estimate of the states over the assimilation window, given the error statistics in the background, observations and model. Various formulations of the weak-constraint objective function can be derived, which possess different characteristics and properties. Here we consider two formulations: one aims to estimate all of the states at each time in the assimilation window; the alternative aims to estimate the initial state and simultaneously the ‘model error adjustments’ over the assimilation window.

We gain insight into the well-posedness of the two formulations, and also the speed of the iteration methods used to solve them, by studying the conditioning of the first order Hessian of the objective function. For our two different formulations of the problem, we derive the structure of the Hessians and establish theoretical bounds on their condition numbers. The behaviour of the conditioning as a function of correlation length-scales, variances and observation configurations is investigated. We show how the conditioning depends on the number of assimilation time steps within a window and hence demonstrate how the different systems behave over longer assimilation windows. We present numerical results to illustrate the behaviour of the two formulations of the problem using simplified models.