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Nonlinear Processes in Geophysics
Discussions
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Interactive comment on "Nonlinear effects in 4D-Var" *by* Massimo Bonavita et al.

Anonymous Referee #1

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This paper contains a discussion of the effects of nonlinearity in the the ECMWF incremental 4D-Var system. Nonlinearity can affect the 4DVar calculation through the nonlinearity of the dynamical model or through the nonlinear relations between some observed quantities and the model state. As new data sources come on stream, the effects of nonlinear observation functionals become more important than they had been previously. Much of the earlier work on nonlinear effects in data assimilation was done with simplified or schematic numerical models, intended to illustrate particular nonlinear phenomena.

In the "incremental 4DVar" methods used widely in numerical weather prediction and elsewhere in the analysis of the ocean and atmosphere, rather than solving the full variational problem all at once, one assumes that the first guess solution, aka the "background," is a reasonably good estimate of the state of the atmosphere, and we may seek small changes to the background state. The assumption that the changes we

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Discussion paper

make are small leads to linearization of model dynamics and observation functionals. This cost minimization subject to the assumption that the increment should be small constitutes the "inner loop."

The fact that the assumption of small increments can be problematical in today's NWP environment is complicated further by the fact that the inner loop calculations are usually done at lower resolution than the main model. This means that, in order to perform the inner loop, the main model state must be transferred to the lower-resolution state in which the inner loop calculations are performed, then, when the inner loop is complete, the resulting increment is projected on the high resolution state space and added to the central forecast. This results in a new high resolution analysis, which is used to compute a new central forecast. A new linearization can then be derived to be used in a succeeding inner loop. As time has gone on, the differences in resolution between the central forecast and the inner loop have increased, and thus the model fields can be extremely rough on the coarse resolution inner loop grid due to nonlinearity of the central dynamical model.

The work described in this manuscript represents an attempt to make quantitative sense of the problem of nonlinearity in the ECMWF forecast system. This is a departure from earlier work on simplified systems. It is obviously much more difficult with the full ECMWF forecast system to investigate quantitative and qualitative dynamics of the atmosphere, as is done in earlier studies. The emphasis here is to try to understand the limitations of the incremental approach, and to investigate the separate effects of model nonlinearity and data nonlinearity. I like this paper very much, and strongly recommend publication in essentially its present form. I would like to see a few points cleared up, and a few things done to make the article more accessible to those not directly involved in NWP.

Comments follow:

P4, line 25: "...a nonlinear dependence of the J_B part of the cost function on the state." The "J_B part of the cost function" is not defined, but I presume, based on common terminology in the literature that the "J_B term" is the first term to the right of the equal sign in (1). That is, of course, quadratic rather than linear. I'm guessing they mean that the nonlinear change of variables leads to a nonlinear dependence of the gradient of the J_B part of the cost function on the state.

P6, line 10 and following, discussion of figure 3: The solid line in figure 3 appears to connect the centers of the circles with the centers of the triangles. This should be noted in the caption. I would be interested to see the prior estimate of the standard deviation, and/or the RMS instrument error, including representation error, marked on that graph. I understand that it might not be so easy to arrive at such numbers.

P6, lines 18-24, discussion of figures 4 and 5: "Figure 4 plots the correlation and standard deviation of these differences . . ." What are the units on the radial axes? Are standard deviations for different observed quantities normalized to give a single number for the total standard deviation? If so, how?

P7, line 1: "The magnitude of the analysis increments is seen to gradually decrease . . ." Can the authors extract a rate of convergence of the iteration process? Given some reasonable set of assumptions, e.g., local convexity of the nonlinear cost function, do we know what rate of convergence to expect?

It is well known that for the cost function based on linearized assumptions, the value of the cost function at its minimum should be a random variable with chi-square distribution on a number of degrees of freedom equal to the number of independent observations. How close do the cost functions discussed here come to satisfying the chi-square test at, say, 95% confidence?

p8, line 11: "No further improvements were seen with further increases in the outer loop count, which points to residual model deficiencies . . ." Another possibility is the observation error, again including representation error. Can it be that the model is already fitting the data within the assumed level of data error?

Figures 6 and 7 need better labels on the ordinate axes. In figure 6, the ordinate axis is labeled “model level.” In figure 7 the ordinate axis is not labeled at all. Please change the labels in both to pressure.

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