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Nonlinear Processes in Geophysics
Discussions

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

Anonymous Referee #2

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The nonlinear aspects of the incremental 4D-Var data assimilation system used at ECMWF are examined in this paper. This is done by comparing the TLM integration with two nonlinear trajectories, by examining the variation in the fit to the observations after each outer loop and by looking at the magnitude of the analysis increments after each outer loop. The impact of the number of outer loops used in the analysis on the forecast skill is also assessed. It is shown that the degree of nonlinearly in the ECMWF 4D-Var has significantly increased between 2004 and 2017 because of the increasing complexity and resolution of the forecast model and because a greater number of observations sensitive to humidity and cloud (i.e. all-sky) are now assimilated.

This article is well suited for the journal Nonlinear Processes in Geophysics. I suggest that this paper requires only minor revision subject to the following comments:

P4, line 24: Holm et al., 2003 should be Holm et al. 2002.

P6, section 4: The experimental design is not clearly defined in this section. The details about the multi-incremental strategy, like the number of outer loops, the horizontal model resolution and the type of simplified physics (dry vs full) in each loop should be described. Part of this information is found in the caption of Fig.6 as well as in section 5 for the operational ECMWF 4D-Var. It would be clearer if all these pieces of information were gathered at the beginning of this section.

P7, line 2-3: It is stated that '. . .the magnitude of the analysis increments appears to be asymptote to a relatively small value. . .' In principle, the analysis increments should converge to zero after a given number of outer loops. Is there an explanation why the analysis increments seem to converge to an asymptote for the temperature and in the stratosphere?

P8, line 29-31: It is stated that the number of inner loop iterations is approximatively 30 for each outer loop and this number is not sensitive to the resolution and outer loop number when using a convergence criterion based on the information content. It is assumed here that a satisfactory convergence is reached for each outer loop. For the experiment with only one outer loop at TL255, is the minimization also stopped after 30 iterations? In this case it is possible that the convergence for all spatial scales may not be reached, which may explain why the results shown in Fig. 13 are much worse for one outer loop than for three and four outer loops. In effect, a degradation of $\sim$20% in Z500 for 12h forecast lead time in the southern hemisphere extra-tropics is surprisingly large. Furthermore, this result seems not sensitive to the degree of non-linearity of the observation operations according to Fig. 13 (linear operators only) and Fig. 12 (all operators). I recall here that the main advantage of the multi-incremental strategy proposed by Veerse and Thepaut (1998) is to find the minimum of the 4D-Var cost function at a lower and affordable computational cost by exploiting the fast convergence of large-scale increments at the beginning of the minimization. The full convergence of the minimization problem for the first outer loops is not necessary since the re-linearization and the change in resolution modify the shape of the quadratic cost

function. Most importantly is the convergence of the last outer loop. The convergence of smaller-scale increments is slower and hence embedded in the inner/outer loops process. For a fair comparison, the total number of inner loop iterations should ideally be the same for the experiments with one and three outer loops ($\sim$90 iterations). This is what it is done in Veerse and Thepaut (1998) where 80 iterations are used for both the one outer loop (80) and four outer loops (4x20) experiments. If only about 30 iterations are used in the one outer loop experiment, then it is important to verify that the gradient norm decreases by at least two or three order of magnitude between the first and last iteration. I suggest that a brief discussion about this issue be added to the text.

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