Hydrol. Earth Syst. Sci. Discuss., 9, C6144–C6152, 2013
www.hydrol-earth-syst-sci-discuss.net/9/C6144/2013/

Hydrology and Earth System Sciences Discussions

Interactive comment on "Ensemble Kalman filter versus ensemble smoother for assessing hydraulic conductivity via tracer test data assimilation" *by* E. Crestani et al.

E. Crestani et al.

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Received and published: 4 January 2013

I find the paper extremely well written, a pleasure to read, and very concise. The study reports potentially valuable results and insight.
Response: first of all, we would like to thank the referee for his/her careful review, which will surely help us improve significantly the paper. In the following, we report the replies to each comment from the referee.

However, the paper can be made substantially stronger by improving the following

issues:
(A) the discussion and conclusions could be supported by some more analysis carried out on the test case results,
Response: we agree with the reviewer that some further analyses would strengthen the conclusions of our study. These analyses are described below in our replies to the detailed comments of the referee.

(B) the test case variance is relatively small (although sufficient to cause a non-linear problem), why not introduce a second test case with some variations in the geostatistics and a larger variance?
Response: following to the referee's suggestions (see detailed comments below), in the revised manuscript we provide the results of one (or maybe two, see reply to detailed comment B.1) additional scenario, in which the variance is changed with respect to the simulations reported in our first submission. Hopefully, these scenarios will further corroborate the explanation on why the EnKF consistently outperforms the ES in this application.

(C) many citations to relevant literature are missing,
Response: in the revised manuscript, we will integrate the cited literature with other references provided by the referees.

(D) some informative details are not provided.
Response: the missing details will be included in the revised version of the manuscript.

DETAILED COMMENTS
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(1) line 8: please insert "approximate" before "Bayesian"

Response: agreed.

(2) page 13092, line 23: please add "marginal" before "transformations".
Response: agreed.

(3) Figure 1: please do not use an interpolated shading for a cell-wise constant field.
Response: agreed.

(4) Figure 3, caption: please correct "untrasformed" to "untransformed".
Response: agreed.

(5) figures 6, 7, 9: please enlarge these figures for better visibility and font size!
Response: agreed.

(A.1) See comments B.1 and B.2 on introducing scenarios with different variance of log-conductivity.
Response: please see our replies to comments B.1 and B.2.

(A.2) Complete results of EnKF and ES always include the estimation variance maps. It will be interesting to see how good the two methods THINK they are, and check that versus reality. Is the reality within the 95% confidence interval of the conditional mean?
Response: we agree with the reviewer that this analysis would complete the evaluation of the performances. In the revised manuscript, we will include variance maps as subpanels of figures 3, 4, 5, and 8.

(A.3) I agree with your statement that the EnKF wins against the ES, because the residual variance decreases from EnKF update to update, so that in the end the remaining fluctuations of concentration and conductivity are small enough to allow the linear and multi-Gaussian approximation. Why do you not analyse and visualize this? For example, you could plot bivariate scatter plots between some concentration value at the expected value of the plume centroid and some conductivity cell, and see how it evolved over time. Initially, you should see a highly non-linear dependence, and an almost linear/bivariate Gaussian one in the end.
Response: in the revised manuscript, we will provide a new figure showing the scatter plots between concentration and hydraulic conductivity at an early and late time for both EnKF and ES in a selected scenario.

(A.4) page 13095, last paragraph: please note that the marginal data distributions fix only the marginal distributions, but not the multivariate dependence. The Kalman-Filter/EnKF/ES assumption is CALLED the "Gaussian assumption", but is is an assumption on multivariate Gaussianity. Thus, it is not only the NST that corrupts the cross-correlation, but there is also a remaining non-multigaussian dependence among all states and parameters.
Response: we agree and will add this comment to the original paragraph.

(A.5) Can you plot how close to "beta" or "log-normal" the concentration data are, and how different the distributions are in space and time? This will help to understand much better why the different transforms perform so differently.
Response: although we agree with the referee on the utility of such a plot, we believe it would not add significantly to the information already given in the manuscript. In particular, while one might find interesting to understand which distribution, whether beta or log-normal, is better fitted by concentration data, we can not see how this would help understand why the two transforms we considered perform so differently.

(B.1) page 13092: If your hypothesis for the different performance of EnKF and ES is true, then you can test it by repeating the test case with a much lower and a much larger variance: in the former case the difference should vanish, in the second case the difference should increase.
Response: we agree with the referee that this test can give a definite confirmation of our hypothesis. In the revised version of the manuscript, we will definitely include a new scenario characterized by low variance. Concerning a second case with a much larger variance, it will probably be unnecessary, as it would probably give results very similar to the ones we already presented. In fact, dealing with early travel time concentration distributions, the lack of Gaussianity affects scenarios characterized also by mild variance values, as the one we discussed.

(B.2) a larger variance is also important to check how far the re-start EnKF can go before it breaks down. This would not mean that you have to double or triple the entire results and discussion section, but some simply summary statistics on the performance under different variances would fully suffice!
Response: in the revised manuscript, we will summarize the results of the new test(s) described above (see B.1) in a new table.

(C.1) introduction, paragraph 1 and 2: the reviews cited here are relatively old. Hence, some methods are missing, such as the Method of Anchored Distributions (http://www.agu.org/pubs/crossref/2010/2009WR008799.shtml). It is fully formal, brute-force numerical Bayes. Hence accurate, but reserved for high-performance computing applications. What about mentioning particle filters?
Response: in our revision, we will add the citation to the Method of Anchored Distributions and reference a few studies on particle filtering used for parameter estimation (see also our discussion on the point C.3 below).

(C.2) page 13086, line 5: A good discussion of the EnKF "abused" for parameter identification is provided by Nowak (2009) in WRR (http://www.agu.org/pubs/crossref/2009/2008WR007328.shtml)
Agreed.

(C.3) as the data transformations play a major role later in the manuscript, they should be brought up in the introduction already. This should trigger citations to Beal et al (2010 in Ocean Science, http://hal.archivesouvertes.fr/hal-00457540/) and to Schöniger et al. (2012 in WRR, http://www.agu.org/pubs/crossref/2012/2011WR010462.shtml) already in the intro, not only in the discussion.
Response: we agree with the referee that literature dealing with data transformation must be included in the Introduction. In the revised manuscript a new paragraph will be added to the Introduction with citations to the papers suggested by the reviewer. This paragraph will also include references to the use of particle filters, which do not require any data transformation (see our comment to point C.1 above).

(C.4) When using data transforms, this is a univariate fix to a multivariate problem. The key problem is not only the marginal non-Gaussianity, but also the multivariate dependence structure between the variables. Therefore, non-Multi-Gaussianity should be brought up in the introduction. Response: we agree with the referee. Our reply is included above at point C.3.

(C.5) To explain the technical difference between EnKF and ES, you can compare those two to Kriging and Sequential Kriging (Vargas and Yeh, 1999 in SERRA, http://link.springer.com/article/10.1007$%$2Fs004770050047?LI=true). That paper proves the identity between step-wise and one-in-all conditioning for the linear /

Multi-Gaussian case. This is an important citation in combination with comment (D.2).
Response: agreed.

(C.6) page 13091, top: this is called the re-start EnKF, and is well-known from the literature. Please provide citations (e.g., http://www.agu.org/pubs/crossref/2008/2007WR006505.shtml ; http://www.spe.org/ejournals/jsp/journalapp.jsp?pageType=Preview\&jid=ESJ\&mid=SPE-92991-PA)
Response: agreed.

(*C.7) page 13091, line 25: L/4 is the recommendation by Ababou et al, 1989 in TiPM (http://link.springer.com/article/10.1007$%$2FBF00223627?LI=true)*
Response: agreed.

(C.8) Particle Tracking with Pollock's method is much older than Salandin et al., 2000. Please add a more fundamental and original citation.
Response: agreed. We will include a citation to the original paper by Pollock.

(C.9) page 13094, line 15: this is a known property of the "parameters-only" EnKF and of the restart EnKF: the state update is done by invoking the governing equations with the updated parameters. Therefore, the parameter-state relation is always physical. This will not be the case in the ES. Please state this fact and remind the reader of the references (see C.6 and C.2)
Response: agreed. We will include this consideration in the revised manuscript.

(*C.10) Another relevant transformation is "Box-Cox", see Kitanidis and Shen (1996 in AWR, http://www.sciencedirect.com/science/article/pii/0309170896000164)*
Response: we do not believe such citation would be appropriate in our context since

Kitanidis and Shen's paper deals only with geostatistical interpolation of concentration data and the authors themselves state that their "methodology is most appropriate when concentration measurements are available on a reasonably dense grid and no additional information (based on modeling flow and transport) can be used". Therefore we have elected not to include such reference as suggested by the referee.

(D.1) page 13087: please mention explicitly that you have no model error here, as otherwise equation (4) would have to look differently.
Response: agreed.

(D.2) top of page 13089: Please mention here that: if the model is linear and all states, errors and parameters are multivariate Gaussian, then both EnKF and ES are exact in the Bayesian sense, and would lead to identical results at the end time of data assimilation. Response: agreed.

(D.3) Equation (7): How do you compute X_t? From particle tracking? Is it true that you look at purely advective transport, no diffusion or local-scale dispersion? I.e., no particle tracking random walk? If you have diffusion/dispersion: what is the Peclet number?
Response: X_t is computed by means of the Pollock's particle tracking algorithm and we do not consider any diffusion or local scale dispersion. I.e., the Peclet number is infinite. We had overlooked these details in our original submission. In the revised version of the manuscript, this information will be included after Equation (7).

(D.4) page 13091, line 19: either the "square root algorithm" is a necessary detail (then provide more information), or it is so marginal that you can drop the entire sentence.
Response: since we consider this detail rather marginal, the entire sentence will be

removed.

(D.5) the number of data used in the test case is not provided. Still, the number of data is relevant to judge how much data is used for how much information gain on the parameters.

Response: for EnKF, the dimension of the measurement vector (number of concentration data assimilated) is 79, 90, 92, 102, 111, 116, 123, 122 at times 0.5, 1, 1.5, 2, 2.5, 3, 3.5, 4 T, respectively. Consequently, the measurement vector in the ES has dimension 79+90+92+102+111+116+123+122=835. In the revised manuscript, this information will be included in Section 3.1.

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 9, 13083, 2012.