Author response to short comment from named referee

Thank you to Pierre Gauthier for reading the manuscript and for his valuable comments. In the following, the referee's comments are reproduced, and my responses are in blue. Please note that I am instructed by the journal to give responses before preparing a revised manuscript, but I highlight here any changes that I plan to make in the revision.

Review of paper The ABC-DA system (version 1.4) : a variational data assimilation system for convective scale assimilation research with a study of the impact of a balance constraint By Ross Noël Bannister Submitted to Geoscientific Model Development Date:

1. MAIN COMMENTS

The resolution of operational NWP models increases and is reaching the convective scale. This raises new issues associated with the inclusion of ever increasing and complex processes. Moreover, this raises new questions regarding data assimilation methods to be used. Petrie et al. (2017) introduced a simple non-hydrostatic model that could even represent explicitly acoustic waves for data assimilation studies. This paper presents a companion variational data assimilation for this model. The paper is well written and focuses for the most part on the modeling of background error covariance. The emphasis is mostly on 3D-var including the so called FGAT (first-guess at appropriate time) which is also used in many operational systems.

In research, one would like to be able to explore different approaches to assess what could be the best one for the assimilation at the convective scale. I was expecting then that the 4D assimilation would have been more prominent, including 4D-Var in strong and weak constraint for example. In the EnVar, the control variable is the complete model trajectory including temporal correlations for the treatment of background error, which is also used in the weak constraint 4D-Var.

How does this approach compares to using the OOPS/JEDI paradigm which can be used with either a "toy " model or an operational one? I think that it would be important for a "community" model that the advantages of ABC-DA be presented from that perspective. Little is said about observation operators which can easily be the dominant component of a DA system. Assimilating large volumes of Doppler radar data is one example. The point I am making is the paper should make an effort to emphasize aspects of the ABC-DA that could entice researchers to use it.

- As I understand it, the JEDI programme is meant to be a resource to share components of data assimilation systems using an object orientated software approach. The ABC-DA system is not generic, nor object orientated as I understand it, but is suited specifically to the ABC model.
- The possible use of observation operators for Doppler will be added to the abstract and to the introduction.
- The possible development of 4DVar will be mentioned in the summary. For this paper though the focus is on background error covariances (as the reviewer mentions below), for which 3DVar is an adequate tool.

As stated line 143, "much of the design of ABC-DA is concerned with how B is modelled". The emphasis is mostly on multivariate 3D-var including the so called FGAT (first-guess at appropriate time) which is also used in most operational system. Bouttier et al. (1997) introduced balance operators obtained from multilinear regression for a covariance model based on homogenous and isotropic correlations for the analysis variables deemed to have uncorrelated error. This corresponds to some extent to what the paper presents in too much details in my view. I do not see the point of explicitly describing how to use the code: this is important but very likely to change with time. This should be included in a user manual or website for users. On the other hand, it would be more important to explain the scientific justifications. Balance appropriate for the convective scale should be discussed: geostrophic balance does not seem to be the most relevant.

- I have provided what I believe to be enough detail for the paper to be in the spirit of the journal. A separate user guide for the code itself exists via GitHub and is referenced frequently in the paper. I hope the reviewer thinks that this is reasonable.
- Geostrophic balance is still present at the larger scales in the system, which are still analysed here. Geostrophic balance is also used, for instance, in the Met Office's variational DA system for their 1.5km grid size model called UKV, so its relevance is worth studying in this paper. Alternative balance relationships are possible, such as the diagnostic relationship given in Sect. 4.3 of [1], which will be explored in future work.

- These scientific justification points (and details about alternative balances) will be made at the end of Sect. 4.2.1 and in the summary.

The paper ends by presenting the results of experiments to illustrate the impact of the different components representing the balance for this particular model. Is the paper about presenting the ABC-DA emphasizing the advantages of the design to study different aspects of DA that may be important for the assimilation at the convective scale? As it is, most of it is to describe what has been implemented for this particular model of B with some results indicating the impact this may have on the analysis.

I recommend that the author reviews his paper to either present ABC-DA as a polyvalent system for research on DA at the convective scale. Or that it is about a multivariate model for B and its impact on the analysis and forecast. Given the large body of literature on this topic, the latter would be rather thin.

- The ABC model and DA system have been developed over the years specifically to explore B-matrix modelling options. I guess this has had an unconscious influence on the emphasis of this paper. I will though mention other possible uses of the system in the introduction (e.g. to explore Doppler observation networks).

The next section presents some specific comments on some, but not all, issues with the paper.

2. SPECIFIC COMMENTS

2.1 Modelling B

- sections 3.4, 4.2, 4.3, 4.4 (∼14 pages) As stated line 143, "much of the design of ABC-DA is concerned with how B is modelled". Sections The emphasis is mostly on 3D-var including the so called FGAT (first-guess at appropriate time) which is also used in most operational system. Early on, it has been recognized that multivariate covariances should embed dynamical constraints such as an approximate geostrophic balance (e.g., see Daley ,1991). Modeling of a "static" B has been the object of many papers that should be referred to Parrish and Derber (1992) presented the first implementation of 3D-Var and introduced a new approach in which the error was divided into balanced and unbalanced components. They used an ensemble of lagged forecasts at 24 and 48-h to represent averaged background error covariances. Bouttier et al. (1997) introduced balance operators obtained from multilinear regression for a covariance model based on homogenous and isotropic correlations for the analysis variables deemed to have uncorrelated error. This is pretty much what is presented in section 4.2. I do not see why the author presents this with so much detail given that this is at best, an example of what could be used in the ABC-DA. Buehner (2005) presents a B based on a EOF representation for stationary covariances that can capture some local effects (e.g., presence of orography).
  - Parrish and Derber will be referenced towards the end of Sect. 3.4. Derber and Bouttier (1999) will be referenced towards the end of Sect. 4.2.1 (I understand that this is the peer reviewed version of Bouttier et al (1997) that the reviewer cites).
  - I have tried to provide as much detail as is necessary to adequately describe the DA system.

2.2 Other comments

- p.7: section 3.3. devotes 7 lines to observations. Later, section 5 gives 8 more lines to the observation operators. This is a bit short in my view.
  - Additionally Sect. 4.5 is dedicated to observation operators. I do believe that an adequate discussion of the observation specifications has been made for this particular paper. More technical aspects of the observation network specifications is provided in the technical documentation, which is cited throughout the paper, and available on GitHub. Further mentions of how the system can be extended to include Doppler wind observations will be made (e.g. in the abstract) to help interest readers who may wish to use the ABC system to investigate observation strategies.
- p.6, line 173: The propagator is said to be difficult to derive so it is replaced by the identity. It has been theoretically defined (LeDimet and Talagrand, 1988) and developed for operational model. Even more, the "transpose" of it has also been developed, the "adjoint model". In the context of the incremental form of 4D-Var, some simplifications to the model can be made regarding resolution or the used of a simplified physics. It would be important to know whether it should be possible to expand the ABC-DA to make it possible to do 4D-Var.

- Reference to LeDimet and Talagrand (1986) will be added to Sect. 3.1 of the paper.

- p.7, line 200: using the analysis variables \delata(x − x_b)= U with B = UUˆT means that we need to get the square root of B but we do not have to invert it. The flip side to this is that if B is singular the increment is built based on the singular vectors of B. For an ensemble like the ETKF, for instance, the increment could only be a linear combination of the members of the ensemble that define B. p.8, lines 207-213: I think this needs to be revised. What is said here only applies to a particular B model with isotropic and homogenous correlations which happens to yield a diagonal matrix when expressed in terms of spectral components (e.g., Fourier, Bessel or spherical harmonics).
  - I will add a short comment here that a singular B-matrix can be modelled using the CVT approach (end of Sect. 3.4). I don't agree with the reviewer that the text applies only to isotropic and homogenous correlations, e.g. if the variances of the spectral components are not just a function of total wavenumber, but of the individual x and y wavenumber components separately, then the covariances can be anisotropic. I will add another short comment (also at the end of Sect. 3.4) that the approach allows more complicated forms of the CVT than $\mathbf{U}_\mathrm{s} = \mathbf{\Sigma}\mathbf{U}_\mathrm{v}\mathbf{U}_\mathrm{h}$.

- p.8, line 224: in the incremental form, there is no need to invert U, insofar as the initial point of the minimization is the background state, in which case, initially, \chi =0.
  - This is true for the first outer loop where $\mathbf{x}^\mathrm{r} = \mathbf{x}^\mathrm{b}$, but strictly speaking $\mathbf{U}^{-1}$ is needed for later outer loops when $\mathbf{x}^\mathrm{r} \neq \mathbf{x}^\mathrm{b}$. The this will be mentioned in the text.

- p.8, line 235: the description of the algorithm does not indicate how \lambda is updated.
  - This is given in step 2(f)v.

- p.9, line 245: I agree that the test of transpose is useful to test specific part of the code. But the gradient test (based on a Taylor expansion) should also be mentioned. It is simpler and is routinely used to validate complex operational variational DA systems when al components are active. It should be mentioned.
  - A comment will be added to Sect. 3.6. The gradient test is now coded and included as part of ABC-DA.

- p.10, line 280: I do not think U-1 is needed.
  - It is needed for the calibration. A comment will be added.

- p.10, line 290: the Helmholtz theorem states that there both a potential component and a rotational one (the streamfunction).
  - Equation (13) is for the rotational part and Eq. (14) is for the irrotational part. These equations (and (23) and (24)) are all derived from the Helmholz theorem, $(\delta\mathbf{u}, \delta\mathbf{v}) = \nabla_\mathrm{h}\delta\boldsymbol{\chi}_\mathrm{vp} + \mathbf{k} \times \nabla_\mathrm{h}\delta\boldsymbol{\psi}$ (∇_h is the horizontal gradient operator and $\mathbf{k}$ is the vertical unit vector), but simplifications arise due to the lack of latitude dependence in this system. The reader will be reminded of this after Eq. (14).

- p.11, line 296: defining the balance operators is a separate exercise that needs more explanation. Using linear regression has been proposed by Bouttier et al. (1997) and used by others. This requires some insight into the type of balance that could exist. At synoptic scales, geostrophic and Ekman balance have been used to guide the linear regression. What kind of stationary balance can we expect at convective scales. Reference should be made to Parrish and Derber (1992) and Bouttier et al. (1997).
  - Reference to Parrish and Derber will be made at the end of Sect. 3.4 (and Gauthier et al, 1999). The peer-reviewed version of Bouttier et al. (1997) (which is Derber and Bouttier (1999)) will be added at the end of Sect. 4.2.1 which discusses the validity of geostrophic (and hydrostatic) balance. Further possibilities for convective-scales will be discussed in the summary.

- p.12, eq.(23): I think the winds cannot be represented as irrotational and this impacts the very formulation of U. Please revise. This impact the form of B as presented in eq.(22). p.14, line 366: I do not think we can represent B as a finite expansion of its eigenvectors, in general. It is a composition of operators that reflect the general form of the balance operators. In the univariate case for example, with homogeneous and isotropic correlations, this would require a large number of eigenvectors to properly represent it particularly if the characteristic scale is small.

- The wind does have a rotational part: Eq. (23) is for the irrotational part and Eq. (24) is for the rotational part in this toy model (see also two points above).
- Only the spatial transforms (vertical and horizontal) are represented as expansions of (approximate) eigenvectors. In the vertical, all 60 eigenvectors are represented (there are 60 levels), and in the horizontal, all 360 wavenumbers are represented (there are 360 longitude points). Hence all scales represented in the model are represented in the DA.

- p.15: section 4.3: one diagnostic used to calibrate the error statistics is to verify if the a priori statistics used in the assimilation are consistent with what is measured from the innovation covariances when real observations are compared to the forecast of a model.
  - A comment that this diagnostic is possible will be added to Sect. 3.6.
- p.15, section 4.3.1: as I understand it, an ensemble of forecasts obtained from the UM is used to define the balance operators. To what extent can we expect those to reflect the balance of ABC forecasts?
  - The UM data are processed to make them consistent with the ABC system, and are then spun-up with an ABC model forecast. I agree that the degree of memory of the UM system has not been tested. A comment will be added to Sect. 4.3.1.
- p.23, eq.(33): given that only a wind potential is used, the multivariate B of eq.(33) needs some explaining.
  - The rotational part of the wind couples to the scaled density field via Eq. (15), which is reflected in (33) (all terms with the α factor).

3. REFERENCES

Bouttier, F., J. Derber and M. Fisher, 1997: The 1997 revision of the Jb term in 3D/4D Var. ECMWF Tech Memorandum No. 238, 54 pages.

Buehner, M., 2005: Ensemble-derived stationary and flow-dependent background-error covariances: evaluation in a quasi-operational setting. Quart. J.R. Meteor. Soc., 131, 1013-1043.

Gauthier, P., M. Buehner and L. Fillion, 1998: Background-error statistics modeling in a 3D variational data assimilation scheme: estimation of the impact on analyses. In Proceedings of ECMWF workshop on diagnosis of data assimilation systems, Reading UK, 2 to 4 November 1998.

References

[1] R.A. Pielke. *Mesoscale Meteorological Modeling.* Academic Press, San Diego, California, 2002.