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Interactive Comment

Interactive comment on "Dynamically constrained ensemble perturbations – application to tides on the West Florida Shelf" *by* A. Barth et al.

A. Barth et al.

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We thank the reviewer for his helpful comments and constructive criticisms. In general, we tried in this reply to explain better how the proposed method for generating ensemble perturbations can be applied beyond the perturbation of the initial conditions.

- *The main focus of the paper is on the generation of perturbations of the initial conditions. In the case of the EnKF, other sources could be considered to generate perturbations: the wind stress, for instance; such a method would not be needed in the case of wind stress errors only. Another potential error source impacting the initial conditions would be downscaling errors; assuming that perturbations or state error EOFs are available on a larger-scale model grid, the land-sea mask part of this approach (Section 3) could be useful while the balance constraints*

(Section 2) would not. So I believe that we are missing a general discussion on the applicability and usefulness of the approach.

Response: The main focus of the paper is not just a method to create perturbations of the initial conditions but also any forcing field such as lateral boundary conditions, atmospheric forcings, bathymetry, bottom roughness, ... for which an a priori linear constraint of the perturbation can be formulated. Since winds are in general close to geostrophic balance, their divergence is small at mid-latitude. A small divergence of the wind forcing can thus be used as a constraint to create an ensemble of wind field perturbations (this example is included in the manuscript).

An error in a nested model can also originate from the lateral boundary conditions provided by the parent model. Ideally, one would create an ensemble of solutions of the outer-model driving an ensemble of nested simulations. Since the cost of creating an ensemble of both models can be prohibitive, one can choose to perturb the lateral boundary conditions (if a one-way nesting approach is adopted). This is the only option if the model is nested in a climatology. Perturbing the various variables from the outer model independently should be avoided since it would lead to inconsistent model results of each ensemble member. The proposed method can be used in this context by requiring for example that temperature and salinity perturbations are compatible with the local slope in a TS-diagram. Also for numerous applications one would require that the velocity perturbations at the boundary are close to the geostrophic equilibrium. If one would require that those constraints have to be satisfied exactly, it is indeed possible to compute the perturbations of one variable and derive the perturbations of the others by using the appropriate linear balance. However, if the linear balance has to be satisfied only to a given extent (which is often the case since they are only approximations), it would be more appropriate to include them as weak constraints with a linear parameter describing how strong the constraint has to be enforced.

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The method can also be applied to perturb model fields such as the bathymetry (which is known to be a large error source for tidal simulation). For example, if a very small area is studied where the resolution of the model exceeds the resolution of bathymetric database, then one can require that the perturbations of the bathymetry should be chosen such that the perturbed bathymetry averaged or interpolated to the resolution of the bathymetry should be equal to the original bathymetry (and possibly allowing some deviations from it). Another approach to perturb the bathymetry following the presented method is to use several bathymetric databases (which often have some discrepancies) and to require that the perturbed bathymetry should be close to all bathymetric databases.

An ensemble simulation can in a first step be used to estimate the expected model error due to those unknown parameters (IC, BC, bathymetry,...). In a second step, improved estimates of those parameters can be obtained by assimilating observations and including the perturbed parameters in the estimation vector.

The manuscript will be updated to include those examples.

- *The main focus of the paper is on the generation of two-dimensional perturbations. In my view, section 3 should be treated as a full 3D problem including the bottom boundary condition (bathymetry).*

  Response: The ensemble generation code is actually written in a way that it can generate n-dimensional perturbations on a curvilinear orthogonal grid. Since the horizontal resolution is much larger than the vertical resolution, grids with terrain-flowing and isopycnal vertical coordinates are usually treated as curvilinear grids (e.g. Shchepetkin and McWilliams 2003). The mathematical development in section 2 uses classical formalism used in data assimilation which allows to express a problem independently from its dimensions. The updated manuscript will mention explicitly that also 3-dimensional perturbations can be obtained.

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Interactive Discussion

Discussion Paper

As an illustration for the discussion, we computed a 3D-perturbation of a tracer T subjected to a weak advection constraint:

$$\mathbf{v} \cdot \nabla T = 0 \tag{1}$$

The tracer is thus a stationary solution to the advection equation. An idealized flow field was assumed,

$$u = ay - bxz \tag{2}$$

$$v = -ax - byz \tag{3}$$

$$w = b(z^2 - 1) \tag{4}$$

which represents essentially a vortex circulation where the divergence (convergence) in the upper part is balanced by the convergence (divergence) in the lower part. The attached figure shows the covariance between a point at the center of the water column and all other grid points obtained using an ensemble of perturbations. This simple example shows how the covariance is aligned along the flow lines and how the upper part and the lower part are correlated in this example by the vertical current in the center of the vortex.

Unfortunately, it is not possible to add a figure to my reply. The figure is available online at `http://gher-diva.phys.ulg.ac.be/Images/wce_eddy.png`.

- *The main focus of the paper is on the generation of instantaneous perturbations. If we wished to implement an approach as in Auclair et al. (JAOT, 2000, not cited in ms.), how would we proceed to penalize the fast transients in (1)? Would we need to include the tangent linear model* M^T *as in Auclair, or an augmented perturbation vector?*

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Response: We think that the most obvious way is to include the tendencies of the tangent linear model as an additional penalty term in the cost function defining the probability of each perturbation (as in Auclair et al). This application with a reference to Auclair et al work will be included in the manuscript. We thank the reviewer for pointing to us the link between Auclair's work and ours.

Specific comments:

- *The interest of balanced perturbations or a proper account of the sea-land mask in the case of the EnKF is mostly apparent at initial time. At subsequent filter integration times, the ECM will have been predicted by the EnKF. If necessary, a Sequential Importance approach could be used to improve the efficiency of the filter if needed.*

  Response: We agree that the evolution of the ensemble covariance matrix is given by the EnFK but it relies on the appropriate definition of the model error introduced at each time step, which depends on the implementation, and it is not defined by the EnKF. The model error introduced at each time step stems from various sources, in particular errors in the lateral and surface boundary conditions, bathymetry, parametrization and discretization errors. While the actual value of the error is obviously unknown, for some error sources an a priori balance can be formulated (see above). The more realistic the perturbation of those forcings is, the more realistic the resulting ensemble will be and the probability that the true model state can be obtained by combining the ensemble members increases. By perturbing thus those fields which are used during the entire model simulation, the effect of balanced perturbations it not limited to the initial time.

- *Most problems can be locally linearized. If the sought perturbations are small (3rd term in (2)), this should not be a problem.*

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Response: We agree with the reviewer, that for small perturbations a useful local linearization can be obtained. Our conclusion, where we describe this as a possible limitation, will be changed to reflect the reviewer comment.

Interactive comment on Ocean Sci. Discuss., 6, 1, 2009.

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