# Estimation of friction parameters in gravity currents by data assimilation in a model hierarchy

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Referee comments by Neil R Edwards

**General comments.** This is the third in a series of papers addressing the important issue of the detailed dynamics of gravity-driven plumes at the bottom boundary of the ocean. Such flows are relatively small-scale and restricted to a few critical locations, very difficult to observe in the ocean or reproduce in the laboratory and challenging to model, but exercise a profound influence on the large-scale flow with implications for global climate. Careful and detailed studies such as this are therefore very welcome. Because of the range of scales involved - the dynamics are driven by small-scale turbulence, but plumes can be coherent over long distances - this is a class of problem where progress demands the application of a hierarchy of models. The two previous papers presented a 2-D nonhydrostatic model of gravity current behaviour and an Ensemble Kalman Filter (ENKF) technique for assimilating observational data into a shallow-water (SW) model of a gravity current. The present paper is the logical conclusion of the study, presenting the application of the assimilation technique to estimate the friction laws acting in the nonhydrostatic (NH) model by fitting the output to the SW model. The paper is therefore interesting as an application of the ENKF to model hierarchies as well as being of direct application to gravity current dynamics. Generally the paper is scientifically clear and thorough and results are well presented. Some questions and comments follow. In particular, the application to model hierarchies beyond this specific case deserves a little more discussion.

**Specific comments.** In applying the ENKF for joint state and parameter estimation, the paper follows the two papers of Annan et al. (2005) and Hargreaves et al. (2004) on the GENIE model, so these might have been referenced. The principal difference is that the GENIE application concerned long-term climate change, for which the critical unknown is the propagation of the structural error covariance far beyond the domain of any calibration dataset. This is fundamentally different from the weather forecast domain but the present application is arguably intermediate in the sense that the true values of model error are observable in the present in principle but largely unobservable in practice. The climate case puts the emphasis on the estimation of structural model error. The GENIE papers fudge this issue, which is dealt with much more rigorously in the Reification approach to model hierarchies of Goldstein and Rougier (2008). It seems the same has happened here and a perfect model seems to have been assumed, using observational error as a proxy (hence the final collapse of the parameter estimate to a point value in the case without ensemble inflation). In other hierarchy applications neglect of structural error would be terminal. How has that affected the modelling and what are the implications? While the model refinement process, including the extra parameters beta and r, is a very useful and important part of the process, would the explicit inclusion of structural error have allowed for progress without these extensions?

Another contrast with the GENIE case is the iterative use of a time series of observations. Does this help or hinder, compared to assimiliating a single dataset of time-averaged values?

Section 4. I find it hard to imagine how turbulent the NH model simulations are. Perhaps it would help to show a velocity or vorticity snapshot, or at least to offer some statistics on the proportion of modelled to parameterised momentum flux contributing to the drag forces being analysed.

Section 5. Similarly at the end of this section, the discussion on disagreement between models and parameter drift could be pinned down quantitatively.

**Technical comments.**
p. 167 l. 3 Why is the integration time limited in this way if the box is periodic? Is at actually spreading that limits runtime cf p. 175?

There are multiple small problems with the English grammar and syntax (eg plurals, incl. data and dynamics). These are too numerous to list, but need attention. Some possible corrections and modifications to clarify the meaning are suggested below:

p. 163 l. 4 "not [simply] to use data …"
p. 163 l. 7 [non-]hydrostatic dynamics?
p. 163 l. 18 "mostly perturbed -> perturbed principally" ?
p. 165 l. 15 "an [inclined] rectangular box"?
p. 165 l. 18 define h(x) here, or did I miss it earlier?
p. 171 l. 19 [measure] typo
p. 179 l. 9 what exactly is meant here?

Appendix
eqn A3 how can this not be a function of ezp(-h/delta), at least before cancellation using beta? And if cancellation via beta occurs, shouldn't A7 look more precisely like A6^2 (I confess I haven't repeated all the algebra myself)
eqn A4 missing "="
eqn A6 missing exp(-z) factor??

**References**
Annan, J.D., Hargreaves, J.C., Edwards, N.R. and Marsh, R. 2005 Parameter estimation in an intermediate complexity earth system model using an ensemble Kalman filter. Ocean Modelling, Vol. 8, pp. 135-154.

M. Goldstein and J.C. Rougier (2009), Reified Bayesian Modelling and Inference for Physical Systems, Journal of Statistical Planning and Inference, 139(3), 1221-1239.

Hargreaves, J.C., Annan, J.D., Edwards, N.R. and Marsh, R. 2004 An efficient climate forecasting method using an intermediate complexity Earth System Model and the ensemble Kalman filter. Climate Dynamics, Vol. 23, pp. 745-760