

Interactive comment on “Estimating the State of a Geophysical System with Sparse Observations: Time Delay Methods to Achieve Accurate Initial States for Prediction” by Z. An et al.

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First, may we thank the referee for the thorough reading of our paper and for the detailed suggestions of changes and improvements. This document is our first response to your comments, and when the discussion period for the paper is completed, we will incorporate our comments here and responses to all commenters into a revised version of the paper. Again, these remarks have been most helpful.

The Authors: An, Rey, Ye and Abarbanel

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1. Techniques for dealing with a sparse observational networks are critically
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important, particularly for ocean and climate reanalyses that attempt to reconstruct the past state of the Earth system (e.g. Compo et al., 2011; http://www.esrl.noaa.gov/psd/data/gridded/data.20thC_ReanV2.html). The experiment scenarios described here by the authors are perhaps most applicable to the estimation of the global ocean state after the introduction of satellite altimeters, e.g. TOPEX/Poseidon in late 1992 (<https://sealevel.jpl.nasa.gov/missions/topex/>), with their final set of experiments having a potential application to leverage data from the Global Drifter Program (<http://www.aoml.noaa.gov/phod/dac/index.php>). Thus from a practical point of view, the time-delay method has potential merit for operational scale data assimilation (DA) and reanalysis.

We have examined the links you provide, and it does indeed look like fruitful directions for the use of the time delay method. We think it fair to evaluate ourselves critically and recognize that we may not be prepared to tackle, with present personnel levels and computational resources, something of this magnitude. However, we agree about the importance of this problem and appreciate your encouraging comments and suggested applications. There is no doubt in our mind that these items are in our future, and we look forward to pursuing them.

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2. Because of such potential, the authors should give a bit more explicit description about how these ideas compare to common methods like 4DVar or the 4D Ensemble Kalman Filter (EnKF), both of which utilize observations over an extended time window. The authors could give a more thorough depiction of how their ideas could be incorporated in these existing systems in order to facilitate a higher likelihood that an operational center might adopt the approach.

Again, we agree in toto with the referee's comments. We have a more cautious path to these comparisons with ExtKF, EnKF, and traditional 4DVar methods [but see our paper in NPG (Improved variational methods in statistical data assimilation J. Ye, N. Kadakia, P. J. Rozdeba, H. D. I. Abarbanel and J. C. Quinn Nonlin. Processes Geophys., 22, 205-213, doi:10.5194/npg-22-205-2015, 2015)) on how we think 4DVar should properly be done]. The comparisons require, in our opinion, another paper dedicated to those, and, if we want to be fair about the comparisons, we feel we need to do them in cooperation with colleagues who have experience with those methods. We do have such colleagues at Scripps Institution of Oceanography, and we will be working with them on just these matters. We considered going into more detail in this paper and decided it might take away from its main point, which was to demonstrate the benefit of using time delays in a simple geophysical model, and its application to drifter measurements.

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3.The sea surface height is closely connected to the near surface currents via the geostrophic balance, particularly in midlatitudes. Thus it is expected that unobserved currents would be well constrained by proper estimation of the surface height. For example, sea surface heights and sea surface winds are used to construct an estimate of ocean surface currents for the OSCAR product (<http://www.oscar.noaa.gov/index.html>). However, the examples given by the authors could perhaps be described as a supplement for the tropical region where this relationship breaks down. For future work, a natural extension would be to address a slightly more sophisticated example consisting of multiple vertical layers and the modeling of the temperature and salinity components of the density. This experiment would give a better test of estimating unobserved variables. For example, observing only temperature while estimating salinity is a challenging problem for ocean reanalyses before the Argo era.

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Thank you for these suggestions. We will look closely at how the geostrophic balance plays into directing the dynamical outcome of our use of time-delays. However, as the geostrophic wind is related to the gradient of the height variable, it may be that this provides a different general constraint on the solutions to the shallow water equations.

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4.A brief statement could be made about the applicability of the time-delay approach, for example, to the tropical observing system of moored buoys (TAO/TRITON). These are stationary sensors generating data about once every 10 minutes, but the majority of this data is not used in DA because most global scale ocean assimilation systems use analysis cycles that span multiple days. Even a coupled ocean/atmosphere DA system cycling every 6 hours could benefit from better use of this data. I suggest investigating the TPOS-2020 (Tropical Pacific Observing System) effort for the potential to inform the future development of this and other observing systems (<http://tpos2020.org>). A weakness in the chosen experiments scenarios that should be acknowledged is that the approach has not been tested on time-delay observations with errors that are correlated in the time dimension. This is particularly important in ocean DA because errors of representativeness often dominate (versus instrument errors).

This is an excellent suggestion. It would appear to provide information from an unused (by us, and it appears many others) data source for useful information about ocean models.

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5.I suggest an experiment, perhaps for future work, in which you run 2 model resolutions. The high resolution run is treated as 'truth', from which observations are drawn. The low resolution model is what you are synchronizing via DA. Set up appropriately, this should give you 'natural' errors of representativeness in the observations that may

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be correlated in time with the errors of future or past observations. Does the time-delay method still work effectively in this experiment scenario?

This is another good idea. We actually considered including such an experiment, to investigate the impact of finite resolution and model errors arising from subgrid scale processes. Ultimately, we decided to leave these considerations for a future paper, and focus here on the perfect model scenario. We see no impediment to the use of time delays in this scenario; indeed, it may provide information from "spatial delays" (also used in the past for nonlinear dynamical descriptions of waves propagating in nonlinear materials) presently not incorporated in our own work.

6. The time-delay method is described in comparison to nudging as a baseline. I would like to see the authors compare a simple 4DVar to the time-delay method as well (via experiment) to give context into how their method compares to a more state-of-the-art DA.

A thorough comparison is planned for a future paper, where we discuss in detail the connection between our method and 4DVar. The revised paper we will prepare notes this as future work. The simple answer at this time is that we know how to introduce time delays into what we call the action, often called the 4DVar cost function, and we have not yet used this augmented cost function (and our method of 4DVar as noted above) on this problem.

7. It seems that the time-delay information for the observations and model state applied with what is essentially a diagonal coupling term emulates a similar effect as the cross-covariances that would in effect apply a non-diagonal coupling term to the innovations

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computed at different times throughout the window. The authors should discuss how the off-diagonal coupling used in most operational DA relates to the diagonal coupling with time-delay observations used here.

We agree with your statements here about the cross-correlations. The off-diagonal terms here arise from the generalized inverse of the time delayed innovations. The diagonal coupling term in time delay space could for instance damp the effect of measurements further in the future, which have more uncertainty due to dynamical instability.

A similar effect could be achieved from 4DVar with a uniform prior and a time distributed observation error matrix, but we would rather discuss this in a future paper that more thoroughly explores the connection between time delayed nudging and 4DVar.

8. The impact of observation error on synchronization via the nudging approach is not addressed very thoroughly. I'd like to see some evaluation of the sensitivity to observation error in the assessment of the method. The authors should describe how their method is impacted by outliers in the observed data. Is the method sensitive to such outliers? I'd like to see an example.

When observation error is present, the model will synchronize to within the noise ball of the 'true' solution, when the model is known perfectly and enough observations are present. We recognize however that for many DA methods the goal is to reduce the RMSE below the noise level, but this was not the case here as we chose to consider the sparsity of observations as the dominant effect, rather than observational noise. As a result, we elected to only include a brief investigation, to show that our method is not significantly impacted by very small observational errors.

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To be clear though, you are right that enough noise will 'break' this method, or at least severely impede its chances of success. The degree of regularization needed for the generalized inverse of dS/dx is commensurate with the observational errors of the system.

In addition to these remarks, we use the synchronization error as our "monitor" of the reduction of the model output error to indicate when we have sufficient observations at each measurement time. These errors are limited by the noise in the observations.

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General Technical Corrections:

We do not comment on these, really valuable "to us" comments. We have addressed each of them in our rewrite of the submitted paper, and on revision after the end of the NPG discussion period, we will note each change we have made built upon these detailed, and appreciated, comments. Thank you.

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