

Reply to Reviewer #3's comments

Title: "Exploring the influence of spatio-temporal scale differences in Coupled Data Assimilation"

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"Exploring the influence of spatio-temporal scale differences in Coupled Data Assimilation" by Garcia-Oliva and co-Authors is a remarkably well-written and well reasoned article on the topical issue of what is the best level of coupling in Earth System DA, specifically Atmosphere-Ocean coupling. The model used in the simulation is very simple (Two components Lorenz 63), however the examination of its behaviour from a dynamical system perspective is thorough and lucid. The examination of how the system behaves in an EnKF DA framework is also informative and well reasoned.

Thank you very much for your encouraging comments and insightful suggestions for improving our manuscript. We provide our responses in blue, while for the proposed modifications to the manuscript, we use **bold** text. We also provide the line numbers from the new, corrected manuscript.

On the other hand, I believe the paper could be significantly strengthened in two directions:

1) One is to add to the discussion a new baseline system where DA is performed independently in the Atmosphere and Ocean and also the forecast step is run in an uncoupled mode. In other words, compare WCDA with an uncoupled DA system. This is useful because WCDA of the Atmosphere-Ocean system is currently run in major NWP Centres and comparing results from the toy model used in this work with results in operational coupled system would validate methodology and applicability of the results presented in this paper about the potential impact of SCDA vs WCDA. For example, the experience in the operational community about the forecast impact of WCDA with respect to an uncoupled baseline has been that forecast impacts are generally small, transient and localised near the interface (e.g., Browne, P. A., et al., 2019. Weakly Coupled Ocean–Atmosphere Data Assimilation in the ECMWF NWP System. *Remote Sensing*, 11(3), 234. <https://doi.org/10.3390/rs11030234>);

R: We agree with the reviewer that the UCDA vs. WCDA is an important discussion, especially in the context where most operational centres are moving toward a WCDA initialisation. Prompted by the Reviewer's comment, we include now some UCDA experiments and discussion in the revised manuscript. The modifications shall be:

Abstract

In 16 – 19: "... case, the cross-updates may become too sensitive to data assimilation approximations. **We further validated that WCDA systematically outperforms uncoupled data assimilation (UCDA) in both components, legitimizing the transition toward WCDA.**"

Introduction

In 39 – 44: “... information on the error terms (Carrassi et al., 2018). **Traditionally, NWP and S2D predictions are initialized using uncoupled DA (UCDA). UCDA consists in the realization of independent data assimilation cycles on each of the relevant components of a coupled model (Meehl et al., 2021). However, when applying UCDA to coupled models, it often results in imbalances between the ocean and atmosphere states, which causes initialization shock and reduces prediction skill (Balmaseda et al., 2009; Zhang et al., 2020). To alleviate such limitations, coupled DA (CDA) is produced with...**”

In 63 – 66: “Our study's main motivation is to explore potential connections between the coupled model's dynamical properties and **the performance of uncoupled and coupled DA methods**, and how the latter interplay with the spatio-temporal scale separation among the model's components.”

In 67 – 71: “We use a low-order coupled system and extensively compare the different approaches for a wide range of temporal and spatial scales and observation configurations. **This can help us to verify when CDA - particularly WCDA - is expected to outperform UCDA, and further anticipate when SCDA is expected to outperform WCDA in an operational configuration, thus legitimizing the allocation of resources to migrate from UCDA to WCDA, or all the way to SCDA.**”

Data Assimilation Experiments

In 211 – 215: “We conduct a set of **coupled and uncoupled DA experiments using the coupled L63 in Eq. (1), and the uncoupled L63-like system in Eq. (5), respectively**, for different values of the parameters S and τ to reflect spatio-temporal separations between the two components of the system. We used the stochastic Ensemble Kalman Filter (EnKF Evensen, 2003) and compared weakly and strongly coupled data assimilation (WCDA and SCDA, respectively). **The additional experiment using UCDA is contrasted against WCDA.**”

Evaluation metrics

In 303 – 309: “For the comparison between UCDA and WCDA, we use the metric $\Delta \text{RMSE}^{\text{UC}}_n$, defined similarly to Eq. (24), but now evaluating the UCDA experiment, thus:

$$\Delta \text{RMSE}^{\text{UC}}_n = \frac{\text{RMSE}^{\text{WCDA}} - \text{RMSE}^{\text{UCDA}}}{\text{RMSE}^{\text{FREE}}}$$

In this comparison, the RMSE for UCDA is computed using the truth and FREE run, both calculated using the coupled L63 system in Eq. 1. The metric $\Delta \text{RMSE}^{\text{UC}}_n$

text{UC}}_n assesses the capability of UCDA to reconstruct the variability of one of the components of a coupled system, using its uncoupled version.”

Results

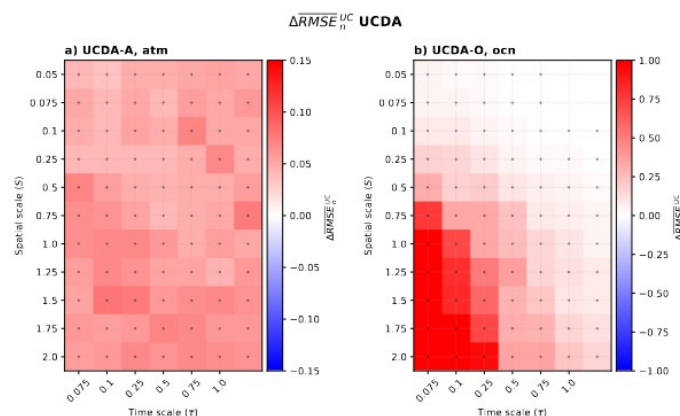
In 312 - 315: “... We also show the comparison between UCDA and WCDA under the FULL observation network. This is, we compare both methodologies under a well-observed system — i.e., observing the (y, Y) variables in each component. Thus, we have UCDA-A and UCDA-O, uncoupled DA in the atmosphere and the ocean, respectively.”

In 316 – 329:

“4.1 Uncoupled versus weakly coupled data assimilation

Figure 10 shows the error of UCDA compared to that of WCDA. In general, UCDA gives larger errors in both components, indicating that using the coupled model for forecasting is useful for propagating information across model compartments and further decreasing the error. The error of UCDA is different on each component, with the ocean presenting the larger difference between UCDA and WCDA.

We can see that in UCDA-A (UCDA in the uncoupled atmosphere, Fig. 10a), the error has approximately the same magnitude across all the spatio-temporal scale separations. On the other hand, the error in UCDA-O (UCDA in the uncoupled ocean, Fig. 10b) shows a clear pattern of increasing error toward the small-slow modes of variability. Since the same pattern is observed when comparing UCDA-O with a partially observed WCDA — i.e. when observing atmosphere or ocean only — (not shown), we can conclude that the coupling is key to further decrease the error growth, via the system’s dynamics. This pattern in the ocean becomes evident due to the dynamic characteristics of the system. The area where UCDA-O performs the poorest is a region where the cross-component correlation is largest (Fig. 4), and the dominant error propagation is ocean → atmosphere (Fig. 8); therefore, the interaction between both components is vital for efficient error constraint, especially in the small-slow modes of ocean variability. This shows that a coupled analysis provides better assimilation”



Concluding remarks

In 394 - 396: “... In particular, we analyze the **so-called uncoupled, weakly and strongly coupled data assimilation** (Penny and Hamill, 2017). **In uncoupled data assimilation, observations are assimilated using an uncoupled system.** In the WCDA...”

In 405 - 408: “ **The coupling between the system’s components is vital for error constraint, and its consideration that is possible in the coupled data assimilation framework provides an effective method for decreasing initial error compared to UCDA. In particular our findings indicate that the ocean is important for atmospheric improvement, as noted by Browne et al. (2019), and the atmosphere-ocean interactions become increasingly important for constraining the ocean’s slow variability.**”

Discussion

In 466 - 471: “One of the key findings of our study is the confirmation of the CDA’s higher potential over UCDA in reducing the error in both components, thereby legitimising the transition toward WCDA. Our results have implications for NWP, indicating that including the ocean improves the initial state of the atmosphere (Browne et al., 2019). In the case of S2D predictions, where the ocean state is the key source of predictability, this transition — UCDA to WCDA — has already been tested (Balmaseda et al., 2009; Penny and Hamill, 2017; Skachko et al., 2019). In this study, we further present implications for the initialisation of slower modes of variability, showing the importance of atmospheric coupling for such time scales.”

2) The observing framework in operational NWP is that of a well-observed Atmosphere and sparsely observed Ocean, which the Authors discuss in Sec. 4.2. This will remain the case for the foreseeable future, even when SWAT altimeters observations become available. For the improvement of weather forecasts in the medium range (1-2 weeks lead time) this is the case that it would be good to see discussed in more detail, possibly in conjunction with a coupled model setup that is realistic for the extra-tropics, i.e. weakly interacting Atmosphere Ocean with the atmosphere dominated by fast, large scale errors and the Ocean with slowly evolving small scale errors.

R: Thank you for raising this issue that we did not address clearly in our initial discussions.

We would like first to clarify that, as our model covers several combinations of spatio-temporal scale separations using weak coupling, we could indeed achieve settings that correspond to an ‘extratropical’ ocean-atmosphere coupling. In fact, our ‘standard configuration’ used for our system’s introduction and description (Sec. 2) with $\tau=0.1$ and $S=1$, pertains to “a weak extratropical coupling between the atmosphere and the ocean, ...” (Peña and Kalnay, 2004).

On the other hand, we agree with the Reviewer that the well-observed atmosphere scenario is more likely in the immediate future, and that atmospheric initialisation is a key component for skilful NWP, a scenario that we neglected in our discussion. Thus, we addressed this topic in our discussion section as:

In 475 – 440: “... Historically, ocean observations have been scarce compared to the atmospheric network (Laloyaux et al., 2018). We **can thus anticipate two situations**: first, that the largest benefit of SCDA is expected in the ocean component, meaning that the large-slow ocean modes of variability can benefit from the high-frequency atmospheric variability, potentially improving seasonal-to-decadal predictions, as shown in Sandery et al. (2020). **Secondly, in the context of NWP, we can infer that WCDA will remain the best strategy for initializing the atmospheric state in medium-range weather forecasts over the upcoming years. The atmosphere marginally benefits from the improved ocean — obtained with SCDA of atmospheric observations. This little improvement is more evident with the configurations where a large and fast atmosphere interacts with a small and slow ocean, characteristic of the extratropics, where the impact of SCDA is negligible compared to that of WCDA.** However, we acknowledge that there has been recent rapid progress in the ocean observation network...”

References:

Peña, M. and Kalnay, E.: Separating fast and slow modes in coupled chaotic systems, *Nonlin. Processes Geophys.*, 11, 319–327, <https://doi.org/10.5194/npg-11-319-2004>, 2004.