Authors' Response to Reviews of

Valid time shifting Ensemble Kalman filter (VTS-EnKF) for dust storm forecasting

Mijie Pang, Jianbing Jin*, Arjo Segers, Huiya Jiang, Wei Han, Batjargal Buyantogtokh, Ji Xia, Li Fang, Jiandong Li, Hai Xiang Lin, and Hong Liao
Geoscientific Model Development Discussions,

RC: ***Reviewers' Comment***, AR: Authors' Response, ☐ Manuscript Text

1. Overview

Response to Editor: We would like to thank the editor for the careful review throughout the whole revision process and all the in-depth comments that help to improve our paper.

2. Comments

RC: ***N is defined later (Line 197). The sentence starting with "N=32" is informal. Please revise this sentence.***

AR: Thanks for the comment. The definition here is removed. The formal definition is put in the following sentence.

> $$[\boldsymbol{x}_1,\ \dots,\boldsymbol{x}_\mathrm{N}] = [\mathcal{M}(\boldsymbol{f}_1,\boldsymbol{w}_1),\ \dots,\ \mathcal{M}(\boldsymbol{f}_\mathrm{N},\boldsymbol{w}_\mathrm{N})]$$
> N refers to the total ensemble number, and the choice will be explained in Section 3.3.

RC: ***Line 199: This sentence should be revised to something like "the ECMWF ensemble forecasts are re-gridded to match the model resolution".***

AR: Thanks for the comment. This sentence is revised as:

> The 6-hourly short-term meteorological forecast field is interpolated to hourly values and re-gridded to match the model resolution.

RC: ***Line 197 and 202 are the same? I suggest to combine these two sentences.***

AR: Thanks for the comment. The former sentence is deleted to avoid repetition.

> Meteorologic field $[\boldsymbol{w}_1,\dots,\boldsymbol{w}_\mathrm{N}]$ are randomly selected from the total 51 ensemble meteorology.

RC: ***Line 230: I suggest removing "pure" since "the pure model forecast" is confusing.***

AR: Thanks for the comment. "pure" is removed throughout the manuscript.

> This position error not only limits the model forecast performance but also significantly degrades the subsequent assimilation analysis and forecast.

RC: ***Line 287: The covariance of the sampling error should be the same as O.***

AR: Thanks for the comment. We meant to refer the variance is the root of diagonal of $\mathbf{O}$. Thanks for point out this mistake.

ϵ^i represents the sampling error vector. It is a random vector subjecting to normal distribution. Its mean is 0 and variance is the root of diagonal from $\mathbf{O}$.

RC: ***Line 467: Please briefly clarify how are the eight central ensemble members selected?***

AR: Thanks for the comment. The sentence is revised as:

These experiments start from 8 ensemble members that are driven by randomly selected emission and meteorology field from the origin ensemble. During the initial assimilation, the extra 4×6 ensemble members from neighboring ±1 and ±2 hours are randomly sampled from these 8 ensemble members. The new ensemble comprises 32 members which is equivalent to the origin ensemble number of *Basic*.

References

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1. Overview

RC: ***The authors have done an excellent job in revising their manuscript. Great job! The manuscript reads well and I am happy with their extensive sensitivity tests. As such, I recommend accepting this manuscript for publication with one minor edit.***

Response to Reviewer #1: We would like to thank the reviewer for the careful review throughout the whole revision process and all the in-depth comments that help to improve our paper.

2. Minor comment

RC: ***In the paragraph starting at line 289, you highlighted the systematic position errors in the free run. That seems out of place in a section that focuses on describing your methodology. Perhaps you should shift that discussion to section 4.1.***

AR: Thanks for the comment. We have re-organized these paragraphs to Section 4.1 to make the discussion more coherent.

4.1 Impact on assimilation analysis

There are noticeable position errors arise with the transport of dust storm. It is clearly shown in Fig. 1 (b,d) that the spatial distribution of the standard deviation (square root of the diagonal values in $\mathbf{P}^f$) from 32 model ensemble members, along with the scatter of absolute model-minus-observation differences in two cases (DSE1, DSE2). In general, their spatial distribution corresponds well to the simulated dust field depicted in Fig. 1 (a, c). Concurrently, the uncertainty in the light blue box decreases rapidly as the simulated dust plume moves southward, as illustrated in panels b.1 and b.2. This suggests that our ensemble model simulations are highly confident that there are less affected by dust aerosols. However, the observations indicate that this area remains heavily polluted. In the case of DSE2, the situation becomes more complex. The simulated dust plume in DSE2 covers most of the observation area with a high dust load, as demonstrated in panels c.1 and d.1. The uncertainty, on the other hand, reveals that the ensemble model is less confident about the dust load, especially in the light blue box displayed in panel d.2. After 3 hours, these discrepancies become more evident. The extent to which this situation affects the EnKF assimilation will be discussed in this paper. It poses a challenge to EnKF assimilation in resolving the high-value measurements in this region.

Subsequent results have confirmed this theory. Figure 4 displays the spatial distribution of ground BR-PM_{10} observations (scatter) and dust field forecasts from the average of the ensemble (panel a.1), the posteriori from EnKF analysis (panel a.2) and EnKF with localization (panel a.3), the average of the enlarged ensemble (panel b.1), the posteriori from VTS-EnKF analysis (panel b.2) and VTS-EnKF analysis with localization (panel b.3) at 11:00, 15th March, 2021 China Standard Time (CST). It should be noted that the average dust concentrations in panel b.1 are calculated from the 160 ensemble simulations used in VTS-EnKF, which slightly differ from the average of 32 ensemble members. In

DSE1, the RMSE and NMB from the pure ensemble model simulation are as high as 856.36 μg $m^{-3}$and -78.31 %. Both EnKF and LEnKF assimilation analyses achieve very limited improvement in estimating the dust state field. As shown in panel a.2 and panel a.3, the RMSE and NMB remain high at 819.04 μg $m^{-3}$and -75.65 % in *Basic*, and 782.57 μg $m^{-3}$and -73.52 % in *L500*. The main reason for this is the ensemble underdispersion, as described in Sect. 3.2. As observed in the light blue box in panel a.1, the simulated dust plume is located farther southeast compared to the PM_{10} measurements. This snapshot exhibits an apparent position error. After EnKF analysis, the simulated dust plume in the light blue box barely changes, as depicted in panel a.2. Numerous ground stations in this area report high PM_{10} concentrations, but the assimilated dust field fails to resolve most of them. The localization method offers limited assistance in this situation, as illustrated in panel a.3. With the unresolved positional error, the EnKF, which focuses more on intensity correction, is much less effective.

References