Improving EnKF spin-up for typhoon assimilation and prediction

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1. Introduction

To initialize the mesoscale EnKF for a regional model, it is common to use initial conditions from the global (re)analysis products and initial ensemble perturbations constructed based on the 3D-Var background covariance. Such initial conditions don't have enough mesoscale information and the perturbations are less than optimal due to the lack of mesoscale flow-dependency. Therefore, EnKF for regional assimilation requires a spin-up period of 2 to 3 days to reach its asymptotic level of accuracy. However, such spin-up period represents a serious obstacle in making use of the observations to achieve satisfactory predictions when the event of interest has a short lifetime or rapid intensification during the development.

To accelerate the spin-up, the "running in place" method proposed by Kalnay and Yang (2010) is implemented within the framework of Local Ensemble Transform Kalman Filter (LETKF) with the Advanced Research Weather Research and Forecasting model (ARW-WRF, Skamarock et al. 2005).

2. Running-in-place (RIP) with LETKF

The LETKF scheme (Hunt et al. 2007) performs an analysis locally in space using local information, including the background ensemble and observations. The analysis corrections ($\overline{\mathbf{x}}_a - \overline{\mathbf{x}}_b$) and ensemble perturbations ($\mathbf{X}_a$) obtained by the LETKF is represented within a space spanned by the local ensemble. The formulas to update the ensemble mean and perturbations at t_n are:

$$\overline{\mathbf{x}}_n^a = \overline{\mathbf{x}}_n^b + \mathbf{X}_n^b \overline{\mathbf{w}}_n^a \quad \text{with}$$
$$\overline{\mathbf{w}}_n = \hat{\mathbf{P}}_n^a \mathbf{Y}_n^{bT} \mathbf{R}^{-1} (\mathbf{y}_n^o - \overline{\mathbf{y}}_n^b) \qquad (1)$$
$$\mathbf{X}_n^a = \mathbf{X}_n^b \mathbf{W}_n \text{ with } \mathbf{W}_n = [(K-1)\hat{\mathbf{P}}_n^a]^{\frac{1}{2}} \qquad (2)$$

In Eqs(1) and (2), $\overline{\mathbf{x}}_n^b$ and $\mathbf{X}_n^b$ are the mean and perturbation of the background ensemble and $\hat{\mathbf{P}}_n^a = [(K-1)\mathbf{I} + \mathbf{Y}_n^b \mathbf{R}^{-1} \mathbf{Y}_n^b]^{-1}$, where K is the ensemble number, $\mathbf{y}_n^o$ is the observations at t_n, $\overline{\mathbf{y}}_n^b$ and $\mathbf{Y}_n^b$ are the background mean and ensemble perturbations in the observational space. Also, $\overline{\mathbf{w}}_n$, $\mathbf{W}_n$ are the computed weight coefficients to linearly combine background ensemble trajectories in such a way that they are closest to the true atmosphere at the analysis time t_n.

The RIP scheme was originated proposed by Kalnay and Yang (2010) to accelerate the spin-up period of the Ensemble-based Kalman filter observed in the absence of prior information about the model state and with limited observations when initializing the assimilation from a state far from the true dynamics (e.g. during a cold start) or when the background error statistics suddenly change (e.g. the rapid regime change of the dynamics). With RIP, the analysis correction and ensemble-based background error covariance are both updated simultaneously to catch up the underlying true dynamics, represented by the observations. The RIP scheme consists of the no-cost smoother (Kalnay et al. 2007, Yang et al. 2009) and an iteration scheme. Details of the RIP method are presented in Kalnay and Yang (2010). The steps for performing RIP are.

1) At t_n, perform the LETKF and derive the weight coefficients ($\overline{\mathbf{w}}_n, \mathbf{W}_n$)
2) Use the no-cost smoother to smooth $\overline{\mathbf{x}}_m^a$ and $\mathbf{X}_m^a$ (at $t_m < t_n$)
3) Perturb $\mathbf{X}_m^a$ with random Gaussian perturbations
4) Evolve the analysis ensemble to t_n

5) If
$$\frac{\left|\mathbf{RMS}(\mathbf{y}_n^o - \overline{\mathbf{x}}_{n,itr-1}^b) - \mathbf{RMS}(\mathbf{y}_{obs} - \overline{\mathbf{x}}_{n,itr}^b)\right|}{\mathbf{RMS}(\mathbf{y}_n^o - \overline{\mathbf{x}}_{n,itr-1}^b)} > \varepsilon \ ,$$
repeat (1)-(4). (itr denotes the iteration number) ε is the chosen threshold to stop the iterations so that we can no longer to extract the information from $\mathbf{y}_n^o$.

3. OSEE experiment setup

In this study, the OSSE experiments are carried out to investigate the potential of the RIP method and the strategy to apply this method to regional data assimilation. The WRF model domain is arranged to cover Taiwan, southeast of China and Japan with 110×110 horizontal grids of 25km. There are 26 vertical sigma layers and the model top is 50 hPa. The experimental period is from 09/14 00Z 2006 to 09/16 06Z 2006. Starting at 09/14 00Z, a set of 37 ensemble forecasts are generated with initial conditions centered at the

National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS) analysis (AVN 1° data) and the ensemble anomalies drawn from the 3D-Var covariance using the data assimilation research test (DART) bed system. Among the ensemble runs, we select the one resulting in a typhoon landed at the northern Taiwan as the nature run (truth) and simulate the observations based on the truth every 6-hour. The observations include 28 radiosondes arranged at the realistic stations and ocean surface wind with locations taken from the QuikSCAT swath at 2006/09/15/09Z, which covers the simulated typhoon. The LETKF-related assimilation experiments are performed with 36 ensemble members with a 6-hour analysis cycle. Localization procedures are done in both horizontal and vertical.

The no-cost smoother is constructed using the weight coefficients computed from the WRF-LETKF system. Results from the model states derived from the no-cost smoother suggest that the benefit of the surface observations can be spread out to the upper levels with the smoother and a lag of three hours (or less) would be appropriate for the linear assumption made in the smoother. Therefore, the RIP experiments in this study use the no-cost smoother with a 3-hour lag. Also, only one iteration is used to first investigate the potential impact of the RIP scheme.

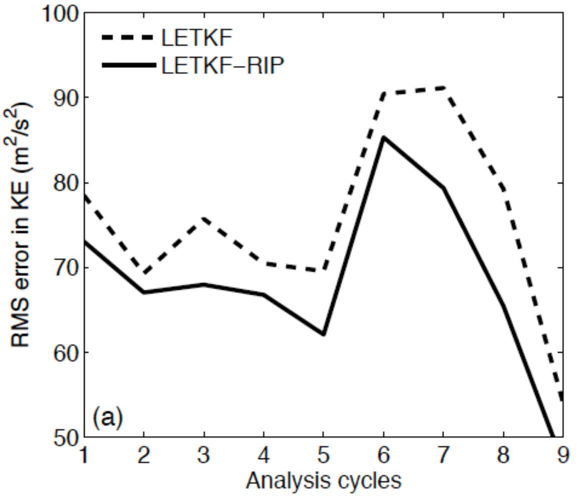
• **Steps for the LETKF-RIP experiment**

1) Computed the LETKF weights at analysis time (00,06,12,18Z)
2) Use these weights to reconstruct the smoothed model ensemble with a 3-hour lag (03,09,15,21Z)
3) Perturb the new model ensemble
4) Take (3) as the new initial conditions and perform the 3-hr ensemble forecasts

4. Impact on Analysis

Figure 1 compares the RMS error of the standard LETKF and LETKF-RIP analysis, in terms of the kinetic energy. Results suggest that the RIP scheme improves the standard LETKF during the spin-up period (the first two days). During the assimilation period, the simulated typhoon in the truth quickly intensified on the 2nd day (09/15/2006), resulting a sudden increase of the RMS error. With RIP, such increase is reduced (Fig.1a). Results show that by this time the vertical structure of the typhoon in the LETKF-RIP analysis had well established with a stronger inner core than the standard LETKF. In addition, the asymmetric component of the typhoon is better represented with the LETKF-RIP analysis.

The most significant improvement is in the mid-upper troposphere (Fig.1b), the data-void region originally. With only one-iteration, RIP provides a significant and useful adjustment for the dynamical structure of the typhoon with the advantage of applying the full nonlinear model integration.



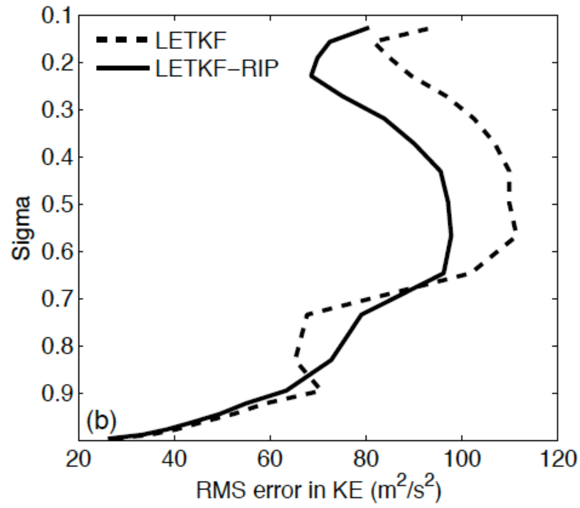


Fig 1(a) Time series of the RMS error of the standard LETKF and LETKF-RIP analyses in terms of kinetic energy and (b) RMS error in vertical from standard LETKF and LETKF-RIP analyses averaged for the 2nd day when the typhoon quickly intensified.

5. Impact on typhoon prediction

In the truth, the simulated typhoon is initially located at the northeast of Philippines with a center pressure of 995 hPa that intensifies to 940 hPa before landfall. It moves northwestward and lands at northern part of Taiwan.

Figure 2 is the typhoon intensity from truth and mean of the ensemble prediction initialized from the LETKF and LETKF-RIP analyses. Results suggest that the predicted typhoon intensity with the LETKF-RIP analysis is always much stronger than the forecast initialized with the standard LETKF analysis. This also implies that the dynamical adjustment brought by the RIP scheme can successfully intensify the development of the typhoon and help to spin-up the overall structure.

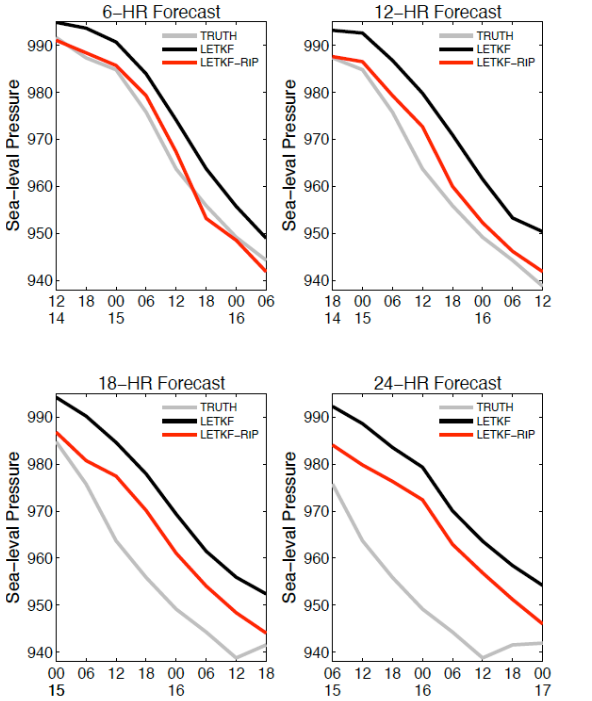


Fig 2 Typhoon intensity from truth and mean of the ensemble prediction initialized from the LETKF and LETKF-RIP analyses at the forecast lead-time of (a) 6-hour, (b) 12-hour, (c) 18-hour and (d) 24-hour.

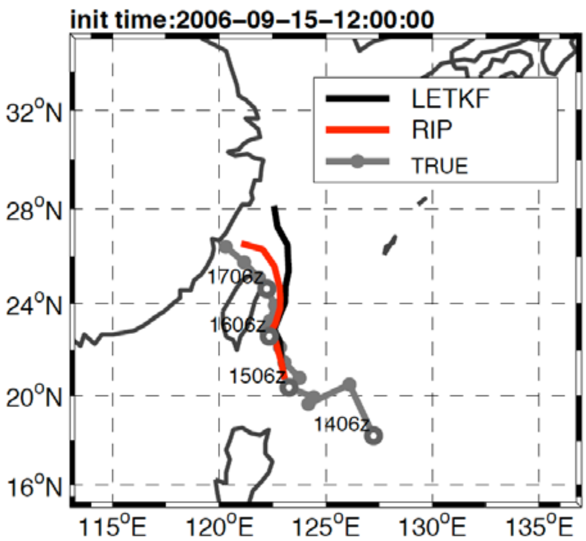


Fig 3 Typhoon track from the truth and mean of the ensemble forecasts initialized from the standard LETKF and LETKF-RIP analyses at 09/15 12Z

During the spin-up period, forecasts initialized from the standard LETKF analyses always result in a typhoon moving northward, without approaching Taiwan. Figure 3 shows an example of the typhoon track with forecasts initialized at 09/15 12Z. With RIP, the northward movement of the typhoon is corrected with the northwestward track. Therefore, the chance to land at the northern Taiwan is greatly increased. This suggests that the dynamical adjustment not only helps to improve the typhoon structure but also the flow condition in the environment.

6. Summary and future work

The running in place method has been implemented in the WRF-LETKF system and tested with only one iteration to investigate its potential impact. Results show that ocean surface wind can be better used and provide more positive impact with LETKF-RIP during the spin-up period, resulting a better dynamical structure of the typhoon. The dynamical adjustment is beneficial to spin up the vertical development of the inner core of the typhoon, showing a stronger intensity in the forecast. In addition, positive impact is identified on predicting the typhoon track.

In RIP, the whole ensemble needs to be re-evolved and thus large computational cost is expected. With this concern, a quasi outer-loop (Yang and Kalnay, 2011), the simplified version of RIP, will be tested in the future.

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