Accelerating the EnKF Spinup for Typhoon Assimilation and Prediction

SHU-CHIH YANG
Department of Atmospheric Sciences, National Central University, Jhongli, Taiwan

EUGENIA KALNAY AND TAKEMASA MIYOSHI
Department of Atmospheric and Oceanic Science, University of Maryland, College Park, College Park, Maryland

(Manuscript received 15 December 2011, in final form 9 March 2012)

ABSTRACT

A mesoscale ensemble Kalman filter (EnKF) for a regional model is often initialized from global analysis products and with initial ensemble perturbations constructed based on the background error covariance used in the three-dimensional variational data assimilation (3DVar) system. Because of the lack of proper mesoscale information, a long spinup period of typically a few days is required for the regional EnKF to reach its asymptotic level of accuracy, and thus, the impact of observations is limited during the EnKF spinup. For the case of typhoon assimilation, such spinup usually corresponds to the stages of generation and development of tropical cyclones, when observations are important but limited over open waters. To improve the analysis quality during the spinup, the “running in place” (RIP) method is implemented within the framework of the local ensemble transform Kalman filter (LETKF) coupled with the Weather Research and Forecasting model (WRF). Results from observing system simulation experiments (OSSEs) for a specific typhoon show that the RIP method is able to accelerate the analysis adjustment of the dynamical structures of the typhoon during the LETKF spinup, and improves both the accuracy of the mean state and the structure of the ensemble-based error covariance. These advantages of the RIP method are found not only in the inner-core structure of the typhoon but also identified in the environmental conditions. As a result, the LETKF-RIP analysis leads to better typhoon prediction, particularly in terms of both track and intensity.

1. Introduction

Initializing an ensemble Kalman filter (EnKF) experiment is a problem that can introduce serious difficulties in numerical weather prediction (NWP). The initial state of the ensemble mean can be derived from operational NWP products, but the initial ensemble perturbations, which represent the “errors of the day,”1 are much more difficult to obtain. The choice of the initial conditions does not usually matter once the EnKF reaches its asymptotic state after a long enough spinup period. However, during the spinup period, the choice of the initial conditions for the ensemble affects not only the accuracy of the analyses and forecasts but also the length of the spinup period (Kalnay and Yang 2010, hereafter KY10). All data assimilation methods suffer from spinup problems; however, the spinup problems tend to be more serious for EnKFs than for variational methods because both the mean and the ensemble perturbations require initial conditions.

In mesoscale NWP, spinup occurs not only at the beginning of an EnKF experiment (a “cold start” from global products) but also can occur repeatedly if there are severe mesoscale disturbances that occur during an experiment. For example, weather radars can suddenly capture severe storms in real time that are missing in the forecast or first guess (Caya et al. 2005). It becomes desirable to spin up the EnKF as fast as possible in order to capture the missing storms. A particularly serious spinup problem exists when cold starting an ensemble in the presence of the generation or rapid intensification period.

1 “Errors of the day” are forecast errors that vary with the day-to-day changes of the dynamical instabilities of the background flow.

Corresponding author address: Shu-Chih Yang, Dept. of Atmospheric Sciences, National Central University, JhongDa Rd. 300, Jhongli 32001, Taiwan.
E-mail: shuchih.yang@atm.ncu.edu.tw

DOI: 10.1175/WAF-D-11-00153.1

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of tropical cyclones; the problem is compounded further if the global forecasts are far from the observed tropical cyclone strength, and if waiting for EnKFs to spin up is not an option.

To minimize the forecast degradation from these cold-start cases, KY10 proposed using a “running in place” (RIP) method, which helps accelerate the spinup of an EnKF and capture missing features in the first guess. The RIP method takes advantage of the “no cost” ensemble Kalman smoother (Evensen 2003; Kalnay et al. 2007), so that it uses the most recent observations to improve the previous initial ensemble states, leading to further improved ensemble states at the current time after observations are assimilated. The process of smoothing, improving the previous initial state, reevaluating the ensemble, and reassimilating the observations can be repeated as long as it is beneficial. During the RIP iterations, the ensemble perturbations respond to the inclusion of the missing features and develop errors of the day in the presence of the features that were missing without the RIP. Like the outer loop of the four-dimensional variational data assimilation (4DVar) method (Courtier et al. 1994; Andersson et al. 2005), the RIP approach improves the nonlinear trajectory of the system and problems that evolve nonlinearly, such as cold-start cases of intense mesoscale weather. Although the iterative approach of the RIP utilizes the observations more than once, which is suboptimal according to linear Gaussian data assimilation theory, KY10 showed that the RIP method is very successful in accelerating the spinup of the local ensemble transform Kalman filter (LETKF; Hunt et al. 2007) coupled with a nonlinear quasigeostrophic model, even in the absence of any a priori information. The implications of using the same observations more than once, as well as a simpler version of the RIP method known as the quasi–outer loop (QOL) for ensemble-based data assimilation, are discussed in detail in Yang et al. (2012, hereafter Y12). Another application of RIP was carried out by Penny (2011), who performed 7 yr of global ocean reanalysis using LETKF with RIP. He found that forecasts from the LETKF-RIP matched the observations much better than using the LETKF with the Incremental Analysis Update (IAU; Bloom et al. 1996) or the Simple Ocean Data Assimilation (SODA), based on optimal interpolation (Carton and Giese 2008).

In this study, the RIP method is applied for the first time to a realistic mesoscale NWP model with a simulated typhoon. To test the usefulness of the RIP, a typhoon with a rapid-intensification stage is chosen so that the cold-start problem is serious. The RIP method is implemented within the LETKF coupled with the Weather Research and Forecasting model (WRF; Skamarock et al. 2005), and tested with simulated realistic observation networks including satellite scatterometer sea surface winds and reconnaissance flight dropsondes. We carry out observing system simulation experiments (OSSEs) in order to initially avoid problems arising from model errors and purely focus on the potential of the RIP method in a mesoscale typhoon situation.

This paper is organized as follows. The RIP method implemented in the WRF-LETKF system is briefly introduced in section 2. Section 3 describes the experimental settings and the implementation of the RIP method in the WRF-LETKF system. The results from the OSSEs with the LETKF and LETKF-RIP systems are presented in section 4. Finally, section 5 provides a summary and discussion.

2. The RIP method within the LETKF framework

As indicated above, the RIP scheme was proposed by KY10 in order to accelerate the spinup period of an EnKF when initializing the assimilation from a state far from the true dynamics (e.g., a cold start) or when the background error statistics suddenly change (e.g., a rapid regime change in the dynamics). With the RIP approach, the analysis correction and ensemble-based background error covariances are both simultaneously updated to capture the underlying true dynamics, as represented by the observations. Details of the RIP method are presented in Kalnay and Yang (2008, 2010). Below, the RIP method is briefly described within the LETKF (Hunt et al. 2007) framework.

Unlike variational analysis methods (3D/4DVar), the LETKF belongs to the class of sequential data assimilation that minimizes the analysis error variance. At each analysis grid point, the LETKF performs data assimilation to update both the mean and perturbations of the ensemble according to the local information of the background (a short-range forecast) and regional observations. In the LETKF, optimal weights are derived so that the linear combination of the ensemble perturbations minimizes the analysis error variance (in the local domain). With K background ensemble members at time $t_n$, the analysis ensemble perturbation (deviations from the ensemble mean) at the analysis time $t_n$ is computed as follows:

$$X_n^a = X_n^b W_n.$$  

(1)

Here, $X_n^b = [\delta x_n^{b,1} \cdots \delta x_n^{b,K}]$ is the matrix of the background perturbations whose columns are the vectors of ensemble perturbations that deviate from the ensemble mean; that is, $\delta x_n^{b,k} = x_n^{b,k} - x_n^b$, where $x_n^{b,k}$ is the $k$th
background ensemble member and \( \hat{x}_n^a \) is the background ensemble mean. Similar definitions are applied to the analysis ensemble mean (\( \hat{x}_n^a \)) and perturbations (\( \hat{x}_n^b \)). The analysis perturbation weight matrix, \( W_n^a \), is computed by

\[
W_n^a = [(K - 1) \hat{P}_n^a]^{1/2},
\]

where \( \hat{P}_n^a \) is the analysis error covariance matrix in the ensemble space, given by

\[
\hat{P}_n^a = [(K - 1)I\rho + Y_n^b R^{-1} Y_n^b]^{-1}.
\]

Here, \( Y_n^b = [\delta y_n^{b,1} \cdots \delta y_n^{b,K}] \) is the matrix of the background ensemble perturbations in observation space, where \( \delta y_n^{b,k} = h(x_n^{b,k}) - h(x_n^{a,k}) \), \( R \) is the observation error covariance matrix, \( h(\cdot) \) is the observation operator that converts a variable from model to observation space, and \( \rho \) is the multiplicative covariance inflation factor. The superscript \( T \) in Eq. (3) stands for matrix transpose, and the inflation coefficient \( \rho \) is constant throughout the assimilation experiments, although adaptively adjusting the inflation factors may further improve the overall performance of the LETKF system (Miyoshi and Kunii 2011; Miyoshi 2011).

The analysis ensemble mean at time \( t_n \) is obtained from

\[
x_n^a = X_n^a W_n^a + x_n^b,
\]

where

\[
x_n^a = \hat{x}_n^a W_n^a + x_n^b,
\]

\[
x_n^a = \hat{x}_n^a W_n^a + x_n^b.
\]

In Eq. (5), \( y_n^o \) and \( y_n^b = h(\hat{x}_n^a) \) are the column vectors for the observations and the background ensemble mean in observation space, respectively.

Equations (1)–(5) provide the basic formulas of the standard LETKF. Based on the framework of the standard LETKF, the RIP scheme includes a no-cost smoother and forward model integrations (KY10). The no-cost smoother is constructed from the weights derived during the LETKF analysis [Eqs. (2) and (5)], which linearly combine the background ensemble trajectories in order to minimize the analysis error variance at the analysis time \( t_n \). If perturbations evolve linearly within an assimilation window, the linear combination of the ensemble trajectories approximates a model trajectory; thus, if this trajectory is closest to the truth at the analysis time, and if model errors are small, this trajectory should also be closest to the truth throughout the window. Therefore, the weights obtained at the analysis time should also be valid throughout the assimilation window (KY10). These LETKF weights allow for the construction of a no-cost smoother for the LETKF, which improves the model ensemble state at an earlier time using observations that are obtained later within the analysis window, without the need of an adjoint model (Kalnay et al. 2007; Yang et al. 2009; see the footnote 1 in KY10 for detailed explanation for no cost). This is equivalent to an ensemble-based Kalman smoother (Evensen 2003, appendix D).

The RIP scheme has two steps: 1) the no-cost smoother is used to update the ensemble states at a time earlier than the current analysis time and (2) these improved ensemble states are forward integrated to the current analysis time and the same set of observations is assimilated. Figure 1 illustrates the setup of the RIP scheme within the LETKF system with a 6-h analysis interval. In loop A, the standard LETKF is performed, defined as iteration zero, to compute the weights for the smoother. Loop B is used to perform the iterations after loop A. In loop B, the smoother is applied at the chosen lag time \( t_{n-6} < t_m < t_n \) to smooth the mean and ensemble anomalies using Eqs. (6) and (7), respectively:

\[
x_m^{a,i+1} = x_m^{a,i} W_m^{a,i} + x_m^{b,i}
\]

and

\[
x_m^{a,i+1} = x_m^{b,i} W_m^{b,i}.
\]

At the \( i \)th iteration, the weights (\( W_n^{a,i} \) and \( W_n^{b,i} \)) obtained during the LETKF analysis computation at \( t_n \) are applied to the mean and the perturbations of the model ensemble at \( t_m (x_m^{a,i} \text{ and } x_m^{b,i}) \). Equations (6) and (7) start at \( i = 0 \), where \( W_m^{a,0} \) and \( W_m^{b,0} \) are the weight coefficients from the standard LETKF (with the observation assimilated once) and \( x_m^{a,0} \) and \( x_m^{b,0} \) are the mean and the perturbations of the forecast ensemble, which is initialized from the final analysis ensemble as derived at the previous analysis time, \( t_{n-6} \). With Eqs. (6) and (7), the updated ensemble at \( t_m \) includes the information at the later time \( t_n \).

Forward integration of the ensemble states from \( t_m \) to \( t_n \) provides the new background ensemble (\( x_n^{a,j+1} \) for
the next iteration. The LETKF computation is then carried out again to obtain the new analysis ensemble \((x_{n+1}^a, w_{n+1}^a)\) and weight coefficients \((w_{n}, W_{n})\). This procedure can be repeated until the difference of the root-mean square of the innovation vectors \((y_{n}^o - h(x_{n}^o))\) is reduced by less than 5%, but in this study the RIP iteration was applied only once to explore its potential impact.

### 3. Experimental setup

#### a. OSSE experimental design with the WRF

The Advanced Research module of the WRF (ARW; Skamarock et al. 2005) used in this study has been widely used to study regional weather predictability (e.g., Zhang et al. 2010; Liu et al. 2007; Miyoshi and Kunii 2011). The LETKF scheme is implemented in this model and the RIP method is constructed based on the WRF-LETKF system. As our first step, OSSEs are carried out in order to investigate the potential of the RIP method and the strategy of applying this method to regional data assimilation.

The ARW (version 2.2) domain is arranged to cover Taiwan, and the area southeast of China and Japan, using a horizontal grid of 150 \(\times\) 150 grid points with a spacing of 25 km. There are 26 vertical sigma layers, with the top at \(\sigma = 0.0065\) (about 50 hPa). The physical parameterization methods include the Rapid Radiative Transfer Model (RRTM) based on Mlawer et al. (1997) for longwave radiation, the Dudhia (1989) shortwave radiation scheme, the Yonsei University (YSU) PBL scheme (Hong et al. 2006), the Kain–Fritsch scheme (Kain 2004) for the cumulus parameterization, and the single-moment microphysics scheme of Lin et al. (1983). These settings are used in all the experiments.

The experimental period is from 0000 UTC 14 September to 0600 UTC 17 September 2006. During this period, a severe tropical cyclone, Typhoon Shanshan, developed in the northwestern Pacific. Starting at 0000 UTC 14 September 2006, a set of 37 ensemble forecasts are generated with initial conditions centered at the National Centers for Environmental Prediction (NCEP) Global Forecasting System (GFS) final analysis (FNL 1° data). The ensemble perturbations are randomly drawn from the 3DVar background error covariance (Barker et al. 2004). The same procedure is used to perturb the NCEP FNL data every 6 h until 0000 UTC 18 September; the tendencies are then computed at the boundaries according to these perturbed states in order to obtain perturbed boundary conditions (Torn et al. 2006). One of the 37 ensemble members is selected as the nature run (truth) for generating the simulated observations for the OSSEs. The initial and boundary conditions of the remaining 36 ensemble members are then used to initialize the assimilation experiments. After each analysis step, the initial conditions for the model are provided by either an LETKF or LETKF-RIP analysis ensemble and the boundary conditions are updated with the newly derived analyses.

Figure 2a shows the typhoon track in the nature run (solid line with circles) as well as the track from the ensemble mean without assimilation (dashed line). We note that among the original 37 ensemble runs, the nature typhoon has a northwestward-curving path while the tracks in the other runs are more northward. In the nature run, the simulated typhoon is initially located northeast of Philippines with a central pressure of 993 hPa at 0000 UTC 14 September, intensifying to 940 hPa before it makes landfall on the northeast part of Taiwan. During the early development stage of the typhoon, strong winds and vertical motion are established in its northern sector, resulting in an asymmetric dynamical structure. Starting at 1800 UTC 14 September, the
eastward component of the low-level environmental wind near the Philippines provides moisture convergence on the southern side of the typhoon. The typhoon quickly intensifies during the period from 0000 to 1200 UTC 15 September, exhibiting a steep eyewall with organized deep convection (e.g., the first column in Fig. 7). During this 12-h period, the central pressure drops by 20 hPa, resulting in the greatest variation in the central pressure throughout its lifetime, as shown in Fig. 2. Correspondingly, the wind speed increases strongly (Fig. 2b, dashed curve), indicating its intensification to a severe tropical cyclone. As the typhoon approaches Taiwan at 0600 UTC 16 September, it slows down and turns westward toward the northern part of Taiwan after 17 September. The modification of the track is likely related to the deepening of the Pacific subtropical high, which results in a change of the steering flow in the environmental condition of the typhoon. This will be further discussed in section 4d, with comparisons with the forecasts initialized from the LETKF and LETKF analyses.

In the following, we investigate the extent to which these dynamical features are represented in the standard LETKF and whether the use of the LETKF-RIP approach during the spinup period of the assimilation experiments (the first 2 days of the assimilation period) can improve the standard LETKF analyses. The analysis variables are the WRF prognostic variables, horizontal and vertical velocities, perturbation potential temperature, geopotential height and water vapor mixing ratio, and perturbation surface pressure of dry air. The analysis cycle interval is 6 h.

Table 1 lists the types of observations used in the OSSEs and their corresponding accuracies. The simulated observations include the sounding data from radiosondes and dropsondes, as well as the ocean surface winds (OSWs) for simulating the Quick Scatterometer (QuikSCAT) satellite data. Figure 3 shows the arrangement of all the types of observations used in the experiments. Simulated observations are generated by adding random Gaussian noise to the variables from the nature run. The rawinsonde (raob) locations are taken from 28 weather stations in the chosen model domain. There are two types of dropsondes, denoted as C130 (U.S. Air Force aircraft) and DOTSTAR (for the Dropsonde Observation for Typhoon Surveillance near the Taiwan Region), which imitate the flight patterns used in the real cases (Wu et al. 2005). The soundings are available below 700 hPa for C130 and 200 hPa for DOTSTAR. The C130 data are arranged in a cross pattern while the DOTSTAR observations are arranged in a circle with a radius of 100 km from the center of the typhoon. To emphasize the influence of the dropsondes, the spatial resolution is higher than the real observations, but they are available only every 24 h. All the sounding data are generated at the model levels.

A fixed observation mask covering the ocean area near Taiwan is selected for generating the OSW observations in order to avoid the issue related to the incomplete coverage of the typhoon due to the limitations of the satellite orbits (see the discussion in Kintisch 2007). The observations are taken at all footprint locations of the QuikSCAT swath at 1200 UTC 15 September, with the “very good” data quality flag. The OSW is generated every 12 h from the wind over the ocean at the lowest level of the model. Data with wind speed greater than 25 m s\(^{-1}\) (gray color in Fig. 3) are masked out as a data quality control to represent the fact that at such speeds the uncertainty of the wind observations becomes too large for it to be useful.

b. Experimental settings and impact of the no-cost smoother

In the control experiment, the standard LETKF is performed with a 6-hourly assimilation cycle with the 36 ensemble members. Other assimilation parameters for LETKF include the constant multiplicative covariance inflation value of 1.08 and a horizontal localization scale of 500 km. This localization scale is chosen to reflect the dense distribution of the OSW, and with this scale, observations have stronger local influence on adjusting the model states during the spinup period.

The LETKF-RIP experiments follow the arrangement shown in Fig. 1 with the standard LETKF serving as loop A. Several modifications from KY10 are made in order to implement the RIP approach within the dynamically complex WRF.
As discussed in section 2, the LETKF-RIP method is made possible by use of a no-cost ensemble-based Kalman smoother (Kalnay et al. 2007; Yang et al. 2009), which makes it possible to improve earlier ensemble states with the information from a later time, including observations and dynamically related flow-dependent error structures. The smoother, valid early in the assimilation window, is built by using the LETKF weight coefficients computed at the analysis time. Here, we first demonstrate the impact of the no-cost smoother by comparing the nature run (left column) with the 3-h forecast initialized from the LETKF analysis (center column), and these forecasts smoothed by the no-cost smoother constructed at the same analysis time (right column). The smoothed values are obtained by applying the weight coefficients computed 3 h later at 0000, 0600, and 1200 UTC 15 September to the 3-h forecasts, initialized from the LETKF analysis, at 2100 UTC 14 September and 0300 and 0900 UTC 15 September. The north–south vertical cross section of the wind speed centered at the typhoon eye is shown in Fig. 4. In Fig. 4, the inner-core structure of the typhoon in the smoothed model states (right column) is significantly intensified compared to the 3-h forecasts, especially at 2100 UTC 14 September and 0300 UTC 15 September, because of the dropsondes or surface winds at 0000 and 0600 UTC 15 September. Figure 4 thus confirms that the observation information at the analysis time can be usefully applied to forecasts that are valid earlier than the analysis time.

For mesoscale phenomena such as for a quickly intensifying typhoon, nonlinear growth of the perturbations becomes large; thus, the linear assumption made in the LETKF smoother may not be valid with a 6-h interval for low-frequency observations such as QuikSCAT. Figure 5 shows the averaged improvement in the vertical for the zonal wind of the model states smoothed by the no-cost smoother at different time lags. The improvement is defined as the root-mean square of the difference between the absolute errors of the smoothed and nonsmoothed zonal winds. The negative (positive) value indicates the improvement (degradation). The results in Fig. 5 suggest that the correction information derived at the analysis time can be useful for the forecasts within 3 h before the analysis time. However, the benefit from the no-cost smoother decreases at the middle levels with longer time lags because observations are limited away from the surface. Thus, a lag of 3 h seems appropriate for the linear assumption made with the no-cost smoother. Therefore, a 3-h lag (rather than a full 6-h lag) is used with the smoother in loop B of the RIP method (Fig. 1) in this study. We should also note that this interval cannot be too short either since the dynamical adjustment of the model state is carried out by evolving the fully nonlinear model; with shorter intervals, the model state would not have enough time to respond to the adjustment (or any other improvement).

With the dynamically complex WRF, it is computationally expensive to perform the RIP simulations with multiple iterations to re-evolve the whole ensemble, as in KY10 and Y12. Therefore, in this study, only one iteration is used to investigate the potential impact of the RIP scheme. Table 2 lists the computational time used to derive the LETKF and LETKF-RIP analyses at 0600 UTC 15 September. The computing time with the LETKF-RIP run is almost double the time used in the LETKF run. Y12 concluded that most of the corrections take place in the first few iterations. Thus, a conservative threshold that uses only one or two iterations can provide significant improvement over the standard LETKF. One RIP iteration, which only doubles the computational cost, should be feasible for operational centers (see the appendix for further discussion).

4. Results

In this section, we focus on comparisons between the standard LETKF and LETKF-RIP analyses and examine...
FIG. 4. Vertical cross sections of the velocity in the north–south orientation of the typhoon from (a),(d),(g) the nature run, (b),(e),(h) the mean of the 3-h forecasts initialized from the LETKF analysis, and (c),(f),(i) these 3-h forecasts smoothed by the no-cost smoother.
the performance of the forecasts in terms of the typhoon track and intensity.

a. Comparison of the error covariance from LETKF and LETKF-RIP

As discussed in section 2, the goal of the RIP method is to improve both the accuracy of the mean state and the structure of the ensemble-based error covariance during the LETKF spinup. Here, we present examples that highlight the differences between the error covariance structures used in the LETKF and LETKF-RIP frameworks.

Two important features in the LETKF-RIP method include using the observations more than once for multistep analysis corrections and re-evolving the ensemble with the nonlinear model. This results in a better dynamical adjustment of the model state as compared to the corrections made by the standard LETKF approach. As suggested by Y12, the dynamical improvement could be especially beneficial for underobserved regions.

Figure 6 shows horizontal slices of the error covariances between the meridional wind speed at the location (22.38°N, 123.27°E, and about 250 hPa) marked with an × and the zonal wind speed on the WRF eta level near 250 hPa. The location chosen is the place with the maximum wind speed in the eyewall of the true typhoon (as indicated with the color shading in Figs. 6b and 6d). Figure 6 shows the error covariance contours, the actual zonal wind error (left panels, shaded), and wind speed of the nature run (right panels, shaded) for the LETKF background ensemble at 0600 UTC 15 September and for the LETKF-RIP simulation after one iteration (i.e., evolved from the smoothed analysis at 0300 UTC 15 September using the observation at 0600 UTC 15 September). The zonal wind error (shaded) is significantly smaller for the RIP run (Fig. 6a versus Fig. 6c). In addition, the error covariance between the meridional and zonal wind components is much better aligned with the dynamical structure of the typhoon in the case of the RIP version as opposed to the standard LETKF approach. The clear improvement in the structure of the error covariance obtained with the RIP method is important since the analysis increments can be improved by the more effective use of observations with the RIP method. Below, we discuss this impact on the typhoon structure on the analysis and forecast states.

b. Comparisons of the LETKF and LETKF-RIP analyses

As seen in Fig. 2b, the typhoon in the nature run rapidly intensifies during the period from 0000 to 1200 UTC 15 September (Fig. 2b), and winds and vertical motion are largely enhanced near the eyewall. Figure 7 shows the vertical cross section of the horizontal wind speed and vertical motion during the rapid intensification of the nature typhoon. The vertical cross section is taken from an east–west slice of the typhoon. As shown in the first column of Fig. 7, the eyewall of the true typhoon is well established at 0000 UTC 15 September, exhibiting organized patterns of deep convection being developed on the eastern side. In addition, strong winds extend to levels above 200 hPa. By 1200 UTC 15 September, the typhoon quickly intensifies to a central pressure of 963 hPa. With these features related to an intensifying typhoon, we first compare how the standard LETKF and LETKF-RIP
simulations represent the typhoon structure during this period.

With the standard LETKF, the typhoon structure is successfully generated from the observational information, but only after assimilating them for 2 days. For example, the central pressure of the typhoon intensifies to 971 hPa at 1200 UTC 15 September when observations are assimilated with the standard LETKF, while, without assimilation, the central pressure of the typhoon in the ensemble mean state is only 995 hPa. The standard LETKF run needs about eight analysis cycles (2 days) in order for its performance to converge to a reliable level that reflects the impact of the observations. Although the typhoon is represented in the standard LETKF analysis, its circulation is excessively broad with a weak intensity. As shown in Fig. 7b, the LETKF analysis at 0000 UTC 15 September is able to exhibit some strong winds on the eastern side of the typhoon, but the eye is too large. With the dynamical information from the OSW data at 0600 UTC 15 September, the eyewall becomes more clearly formed in the low levels, including a shrinking of the eye at low levels. However, the vertical development is not apparent until 1200 UTC 15 September. As expected, the typhoon’s intensity is still weak, and its central pressure at 1200 UTC 15 September is only 971 hPa as compared with the true typhoon (963 hPa; Fig. 7g). Therefore, the improvement with the standard LETKF approach is not quite significant enough, so that the vertical structure of the typhoon is still not correct. We should note that during the LETKF spinup period (14–16 September), the typhoon is developing over open waters where rawinsondes are sparsely distributed. Therefore, the impact or adjustment of the typhoon inner structure can be attributed...
FIG. 7. Vertical cross sections of the velocity and wind speed in the west–east orientation of the typhoon from (a),(d),(g) the nature run and the (b),(e),(h) standard LETKF and (c),(f),(i) LETKF RIP analyses.
to the OSW and dropsonde data. During the early assimilation period, the positive impact of observations like the OSW is limited to the lower levels, and the asymmetric character of the LETKF typhoon is much less pronounced than the true dynamical structure (cf. Figs. 7d and 7e). In addition, the results from this control experiment reflect that the representation of the typhoon structure in the analysis is associated with the availability of the observations. With only a limited amount of observations available, it takes more time to spin up the cyclonic circulation of the typhoon.

Given the same amount of observations, the differences between the LETKF and LETKF-RIP analyses reflect the dynamic modifications on the typhoon structure after loop B (RIP iteration) is included. The eyewall structure in the LETKF-RIP analysis is already better represented at 0000 UTC 15 September and quickly develops at 0600 UTC. At this time, the typhoon structure in the LETKF-RIP analysis is significantly improved, particularly regarding the intensity on the eastern side of the typhoon. The LETKF-RIP method helps to better represent the dynamical structure at the middle to upper levels (600–200 hPa). Also, in comparison to the excessively outward tilting eyewall in the LETKF analysis, the LETKF-RIP typhoon exhibits less tilting in its steep eyewall. This indicates a much stronger vertical development and represents a mature structure of the typhoon. In the bottom panel in Fig. 7, the maximum vertical velocities at 1200 UTC 15 September are 1.14, 0.44, and 2.38 cm$^{-2}$ for the nature run and the LETKF and LETKF-RIP analyses, respectively. In addition, the central pressure of the typhoon in the LETKF-RIP analysis at this time is 965 hPa, comparable to the true typhoon. The results from LETKF-RIP suggest that the nonlinear integration in loop B plays an important role in adjusting the dynamical structure by making better use of the model dynamics so that features of asymmetry and the untitled core are particularly well represented in the LETKF-RIP analysis.

To further examine whether the LETKF-RIP method is better able to represent the typhoon structure during the LETKF spinup period, a domain of 1000 km × 1000 km, centered at the true position of the eye of the typhoon, is used to compute the RMS error in order to emphasize the results for typhoon assimilations. Figure 8 shows the results; here, Figs. 8a and 8b indicate the time series of the RMS errors in terms of the kinetic energy (KE), averaged over the lower and upper levels, respectively, and Fig. 8c shows the vertical distribution of the mean KE RMS errors at the model levels, averaged over the first 2 days (eight assimilation cycles). The lower levels are defined as the lowest nine model levels ($\sigma < 0.73$, roughly below 750 hPa), and the remaining levels make up the upper levels. We note that without data assimilation, the RMS errors at the low levels start at 160 m$^2$ s$^{-2}$ and double in just 1.5 days (not shown).

The results in Figs. 8a and 8b indicate large growth in the RMS errors from 0600 to 1200 UTC 15 September, when the typhoon rapidly intensifies. The errors are larger for the standard LETKF results, because the model is less able to represent the strong winds and vertical development of the typhoon structure. In other words, the rapid change of the typhoon strength is not well captured during the LETKF spinup. In contrast, the LETKF-RIP method shows significant improvement, especially during the rapid intensification of the typhoon and in the troposphere above the boundary layer for $0.2 < \sigma < 0.9$. Improvement is found not only in the inner core of the typhoon, as shown before in Fig. 7, but also in its environment. Furthermore, the model states of the LETKF-RIP approach benefit from the forecast length of 3 h in loop B and thus have time to adjust to the dynamical evolution represented by the observations. We also tested reducing the lag of loop B to 1 h (not shown), and the results indicate that the improvement is then limited to the low levels and fades away for levels away from the surface.

The improved wind fields in the LETKF-RIP analysis further enhance the convergence and moisture transport into the inner core, resulting in a stronger vertical circulation pattern. Therefore, the efficiency of the “heat engine” behavior of the typhoon is amplified. These results suggest that the typhoon structure in the LETKF-RIP analysis has been spun up by adjusting the dynamical structure, by effectively using the observations, and by the re-evolution with the nonlinear model. This is done without using a bogusing procedure (Kurihara et al. 1993; Zou and Xiao 2000; Pu and Braun 2001), as is widely done to initialize typhoon simulations and predictions.

c. Comparison of the typhoon predictions

In this section, we evaluate the performance of ensemble forecasts initialized from the analyses in section 4b, in terms of the intensity and track of the typhoon.

In the nature run, the typhoon slows down as it approaches Taiwan at 0600 UTC 16 September and starts to turn westward, as shown in Fig. 2. During early assimilation cycles with the standard LETKF model, the predicted typhoon track curves northward (e.g., the blue lines in Fig. 9), instead of heading toward Taiwan as the track from the nature run (gray line). After assimilating observations for six more analysis cycles, the northward
movement is corrected: after the analysis on 0000 UTC 16 September, the typhoon is predicted to make landfall in the northern part of Taiwan. In other words, the probability of it making landfall in Taiwan is low before 16 September, according to the standard LETKF analysis. Figure 9 shows a comparison of the track predictions initialized from the standard LETKF and LETKF-RIP analyses on 15 September. As seen in Fig. 9, the westward turning of the typhoon appears earlier in the LETKF-RIP predictions and is more enhanced after more observations are assimilated. The LETKF-RIP forecast, initialized at 1200 UTC 15 September, successfully predicts the typhoon track curving westward, 12 h earlier than the LETKF prediction. The reasons for this change will be investigated further in the following subsection.

The prediction of the typhoon intensity also benefits from the analysis correction derived from the LETKF-RIP method. Figure 10 shows the predicted intensity of the typhoon from the mean of the ensemble forecasts as initialized from the first 2 days of the assimilation period (0600 UTC 14 September–0000 UTC 16 September). The predicted intensity from both the LETKF and LETKF-RIP analyses is weaker than the nature run, and the discrepancy from the nature run increases with the length of the forecast. Nevertheless, the advantage of
FIG. 9. Track prediction initialized on 15 Sep 2006 with the standard LETKF (blue line) and LETKF-RIP (red line) analyses at different times. The gray line denotes the typhoon track from the nature run.
the LETKF-RIP method over the LETKF version is basically persistent. The LETKF-RIP analysis consistently predicts stronger typhoon intensities than does the LETKF method, suggesting that the adjustments on the initial states significantly affect the dynamical structure of the typhoon and benefits the typhoon prediction. We note that the advantage of the LETKF-RIP approach does not grow or shrink for the longer forecast up to 24 h. Since the observations to retrieve the 3D dynamical structure of the typhoon and its environment are limited, the improvement of typhoon intensity prediction at longer lead times remains restricted.

Since all of the experiments used the same number of observations, results from Figs. 9 and 10 indicate that the RIP method has the potential to use observations more effectively and has a better chance of adjusting the typhoon structure for a better prediction during the EnKF spinup. As could be expected, the advantage of the LETKF-RIP method diminishes for
the prediction initialized at 0000 UTC 16 September since, after the spinup period, the performance of the LETKF analysis has converged, and the ensemble perturbations are able to represent the flow-dependent error structure, so that the ensemble-based error statistics are reasonable for assimilating observations. Therefore, after the LETKF has spun up, the LETKF-RIP run can no longer extract more information from the same observations.

d. The westward shift in the LETKF-RIP forecast from 1200 UTC 15 September

In Fig. 9c, it is evident that the typhoon in the prediction initialized from the LETKF-RIP analysis at 1200 UTC 15 September is the first cycle time where a pronounced westward shift is seen in the typhoon’s track, in better agreement with the nature run. We investigate the differences in this case between the forecasts initialized from the LETKF and LETKF-RIP analyses in order to understand the dynamical adjustments related to the typhoon track brought by the LETKF-RIP simulation. We note that the true typhoon exhibits a northwestern movement during the first 24-h forecast and then turns westward after 1200 UTC 17 September. During the first 6-h forecast (1200–1800 UTC 15 September), more than half of the LETKF-RIP ensemble members (25 out of 36 members) have the typhoon move northwestern while there are only 10 members of the LETKF members without the RIP simulation moving in that direction. As a result, the mean of the LETKF-RIP ensemble prediction shows that the typhoon turns earlier as compared to the LETKF prediction.

In general, the large-scale environment controls the movement of a typhoon, including its direction and speed. The translation speed of the true typhoon (the black line in Fig. 11a) slows down as it approaches Taiwan between 0600 and 1200 UTC 16 September, as indicated in the gray zone in Fig. 11. We note that the typhoon track for both the LETKF and LETKF-RIP ensembles is particularly divergent during this period. This implies that the typhoon movement is at a critical changing point. In particular, the typhoon in the LETKF prediction moves too fast compared to that of the LETKF-RIP prediction. This indicates that the steering flow for the typhoon (and its environmental conditions) is not well represented in the LETKF ensemble. In comparison, the LETKF-RIP prediction indeed captures the deceleration of the typhoon movement during 0600–1200 UTC 16 September.

We define the steering flow for the typhoon as the averaged horizontal wind velocity within a radius of 500 km from the typhoon eye at the model levels from \( \sigma = 0.83 \)-0.16, approximating constant pressure levels of 850 and 200 hPa, respectively. Figure 11b shows the zonal (with circles) and meridional (with squares) components of the steering flow vertically averaged for these levels. Figure 11c shows the vertical distribution of the steering flow at the model levels of \( \sigma = 0.83, 0.65, 0.50, \) and 0.27. At the initial time, 1200 UTC 15 September, the steering flow for the true typhoon is dominated by the northward wind related to the circulation of the Pacific subtropical high. During the first 12-h forecast period, a westward component appears at low and upper levels, making the true typhoon move northwesterly. From 0600 to 1200 UTC 16 September, the steering flow at low levels changes to eastward, resulting in a slowdown of the typhoon’s northwesterly movement. Due to the strong northward component in the upper levels at this time, the typhoon continues to move northward. After 0600 UTC 17 September, the westward component becomes enhanced (as indicated in Fig. 11b with the black line with circles), resulting in a more westward track, which deflects the typhoon to northern Taiwan.

Figure 11c also shows an eastward component in the steering flow in the LETKF-RIP forecast related to the slowdown of the typhoon movement during the critical turning period, especially at the lower levels at 1200 UTC 16 September. It also starts to have a westward component after 1200 UTC 17 September at the low level of \( \sigma = 0.83 \). Although this happens later than with the true typhoon, the typhoon in the LETKF-RIP forecast is still able to turn westward.

In contrast, the steering flow from the LETKF forecast does not have the eastward component at low levels during the period from 0600 to 1200 UTC 16 September. Additionally, the northward wind above the midlevels is stronger than the nature or LETKF-RIP forecasts, showing no deceleration of the typhoon in the LETKF prediction. As shown in Fig. 11b, the stronger northward steering flow (indicated by the blue line with squares) increases during the forecast period, causing the typhoon in the LETKF forecast to move faster and more northward than the true one and that in the LETKF-RIP forecast (e.g., comparing the arrows in Fig. 12). This excessively strong northward component in the steering flow in the LETKF forecast can be attributed to the orientation of the Pacific subtropical high. Compared to both the nature run and LETKF-RIP forecast, the Pacific subtropical high in the LETKF forecast does not extend as far westward. Therefore, the relatively low geopotential height appears to the northeast of the typhoon in the LETKF forecast (contours in Fig. 12a). As shown in Fig. 12a, an excessive northward wind component is exhibited on the northeast side of the typhoon in the LETKF forecast. Such differences, in the geopotential height and winds, are reduced in the LETKF-RIP
These results suggest that the typhoon movement is better depicted by the LETKF-RIP prediction because the environmental representation is closer to that of the true typhoon. We also note that, in Fig. 12, large differences near the typhoon circulation are related to the displacement of the typhoon locations in the forecasts from the one in the nature run.

5. Summary and discussion

In this study, the RIP method proposed by KY10 for accelerating the spinup of EnKF is implemented with the WRF-LETKF system and tested for the purpose of improving typhoon assimilation and prediction with OSSEs. It is assumed that only a realistically small number of radiosondes and dropsondes and ocean surface winds are available for assimilation.

The main idea of the RIP method is to improve the ensemble model states during the EnKF spinup by repeatedly using observations to adjust the nonlinear dynamics of the model evolution toward the true dynamics. There are two important components in the RIP method: the no-cost smoother, which allows for adjustments to the model states at an earlier time, and
the full nonlinear model that recalculates the nonlinear forward integration. The no-cost smoother is built based on the weight coefficients derived from the LETKF computation, with the information from observations and the flow-dependent dynamical error structure at the current analysis time. In this study of typhoon assimilation, the implementation of the RIP method is modified, given considerations of strong nonlinearity of the mesoscale dynamics and computational cost. The LETKF-RIP method, coupled with the dynamically complex WRF, uses two loops with different integration intervals: loop A performs the regular 6-h forecast and the LETKF analysis at the analysis time, and loop B uses the no-cost smoother to adjust the model ensemble states 3 h prior to the analysis time, re-evolves the ensemble states, and finally re-assimilates the same set of observations at the analysis time. Our results confirm that the RIP procedure improves not only the ensemble mean, but also the structure of the flow-dependent ensemble error covariance, which is relevant to the evolution of the underlying evolving dynamics.

Based on the typhoon structure in the analyses and forecasts, the above results confirm the advantage of the LETKF-RIP method over the standard LETKF approach for more effective extraction of information from the observations during the early stages of the assimilation. The LETKF-RIP analysis exhibits a more intense typhoon structure, including a stronger and more organized eyewall and an asymmetric structure. As a result, the LETKF-RIP analysis is better able to represent the rapid intensification of the typhoon, whereas for the standard LETKF, the analysis error grows rapidly during the intensification period (0000–1200 UTC 15 September). The significant improvements shown at the middle to high levels suggest that the RIP method is able to provide useful dynamical adjustments through the nonlinear model integration for typhoon development.

The corrections introduced by the LETKF-RIP technique involve not only the typhoon’s dynamical structure but also the environmental conditions determining the steering flow for the typhoon track. With a 12-h lead time, the typhoon prediction initialized from the LETKF-RIP analyses predicts the westward movement when approaching Taiwan, which is associated with a better depiction of the steering flow. In addition to the track prediction, the typhoon intensity is persistently stronger and better captured in the LETKF-RIP prediction during the developing stage, although the impact is most apparent in the first 12-h forecasts. Nevertheless, LETKF-RIP makes a more effective use of limited observations to improve its typhoon intensity prediction.

The dynamical adjustment from the LETKF-RIP method for the environmental steering flow is further examined in a case study of a forecast initialized at 1200 UTC 15 September. Results suggest that the steering flow for the typhoon in the LETKF-RIP forecast better captures the change in the direction of the flow associated with the slowdown of the true typhoon movement and the northwestward turning track. In comparison, these features are not shown in the LETKF forecast. The steering flow for the typhoon from the LETKF-RIP forecast has an overly strong northward component in the steering flow due to the reduced westward extension of the Pacific subtropical high, resulting in the typhoon moving quickly northward. The results from this case study suggest that the RIP procedure can both improve the structure of the inner core of the typhoon and the large-scale environment, resulting in a better forecast of the typhoon.

FIG. 12. (a) The difference in the meridional wind (color) and geopotential height (contour) between the LETKF 2-day forecast and nature run at 1200 UTC 17 Sep. (b) As in (a), but here the difference is derived with the LETKF-RIP 2-day forecast. The center of the typhoon is denoted by a plus sign (+) and its moving direction is denoted by the arrow (black for the nature, red for LETKF-RIP, and blue for LETKF).
The success of the RIP method demonstrated in this study suggests that the nonlinear evolution of the ensemble has an important influence on the LETKF performance, as it determines the mean state and the corresponding uncertainties. The RIP method can act as an ensemble-based outer loop to adjust the nonlinear evolution of the ensemble. However, the RIP method requires more computations because the nonlinear patterns of evolution of the whole ensemble state are adjusted (re-evolved with the model). With the settings used for the LETKF-RIP method in this study, the computational cost is double that of the standard LETKF approach. In fact, one RIP iteration provides the most useful improvement in this study and adding iterations does not significantly further improve either the track or the intensity prediction of the typhoon (see the appendix). We also note that an alternative would be to use the simplified version of the RIP technique, the quasi–outer loop (QOL), as proposed by Y12, to achieve similar effects by improving the nonlinear evolution of the mean state. Furthermore, as shown in Y12, the RIP or QOL methods could be useful beyond the spinup period when the background error becomes nonlinear due to rapidly growing instabilities or for nonlinear assimilation windows with relatively few observations. Such a strategy would be similar to the outer loop used in variational systems.

Although the OSSE setup used for investigating the impact of the RIP scheme is idealized, the results provide guidance about how to optimally use limited observations available during the EnKF spinup period and during the early and rapidly developing stages of tropical cyclones. The results suggest that the dropsondes and scatterometer winds could provide additional valuable information about the development the typhoon structure with the RIP algorithm, allowing the ensemble used in the EnKF simulations to appropriately reflect the uncertainties related to the underlying evolving dynamics. The RIP method is currently being tested for the EnKF spinup with real observations with inhomogeneity and different accuracies. Preliminary forecasts initialized from the LETKF-RIP analysis with real observations show that the RIP approach has a large positive impact on the typhoon track prediction during the development stage of 2008's Typhoon Sinlaku. The RIP scheme can still be very beneficial when dealing with the dense observations, without having the issue of an underdispersive ensemble.

Acknowledgments. We thank the WRF/WRF-VAR development teams and the Data Assimilation Research Test Bed group at NCAR, as well as Prof. Chun-Chieh Wu from National Taiwan University and Prof. Ming-Jen Yang from National Central University, for their valuable suggestions. We would also like to thank Ai-Lin Hsiao and Chih-Yin Chen for their technical support. S.-C. Yang is sponsored by the Taiwan National Science Council, Grant 98-2111-m-008-014. This research was supported by the Center for Computational Geophysics of National Central University (NCU-CGG99-0008) and partly supported by the Office of FIG. A1. Track prediction initialized from the standard LETKF (blue line), LETKF-RIP (red line), and LETKF-RIP2 (green line) analyses at (a) 0000, (b) 0600, and (c) 1200 UTC 15 Sep 2006. The gray line denotes the typhoon track from the nature run.
Naval Research (ONR) Grant N000141010149 under the National Oceanographic Partnership Program (NOPP).

**APPENDIX**

The WRF LETKF-RIP with Multiple Iterations

A new experiment is conducted in order to evaluate the impacts of using multiple iterations for the LETKF-RIP method with the WRF. This experiment is performed using two iterations with the LETKF-RIP approach during the period from 0000 to 1200 UTC 15 September when the typhoon in the nature run rapidly intensifies. Hereafter, the LETKF-RIP experiments with one and two iterations are referred to as LETKF-RIP and LETKF-RIP2, respectively.

Results show that LETKF-RIP2 provides some further adjustment with one more RIP iteration, but, overall, the dynamical structure of the typhoon and its environment are not significantly different from the LETKF-RIP analysis. Figure A1 shows the typhoon track prediction initialized from the LETKF, LETKF-RIP, and LETKF-RIP2 analyses. Results indicate that the typhoon tracks in the LETKF-RIP2 forecasts are not significantly different from the ones derived with LETKF-RIP. When initialized at 0600 UTC 15 September, the track prediction from LETKF-RIP2 at longer forecast lead time is slightly improved from that with LETKF-RIP. This may be due to the large amount of observations available at this time. Also, there is no apparent modification for the intensity prediction. Results from the LETKF-RIP2 experiment suggest that it would be preferable for the operational center to use one RIP iteration to achieve the most important adjustment, given the heavy computational cost of re-evolving the whole ensemble required in the LETKF-RIP scheme.

**REFERENCES**


