A New Typhoon Bogus Data Assimilation and its Sampling Method: A Case Study

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Abstract In this study, the authors introduce a new bogus data assimilation method based on the dimension-reduced projection 4-DVar, which can resolve the cost function directly in low-dimensional space. The authors also try a new method to improve the quality of samples, which are the base of dimension-reduced space projection bogus data assimilation (DRP-BDA). By running a number of numerical weather models with different model parameterization combinations on the typhoon Sinlaku, the authors obtained two groups of samples with different spreads and similarities. After DRP-BDA, the results show that, compared with the control runs, the simulated typhoon center pressure can be deepened by more than 20 hPa to 30 hPa and that the intensity can last as long as 60 hours. The mean track error is improved more than 20 hPa to 30 hPa and that the intensity can last as long as 60 hours. The mean track error is improved after DRP-BDA, and the structure of the typhoon is also improved. The wind near the typhoon center is enhanced dramatically, while the warm core is moderate.

Keywords: typhoon, DRP-4-DVar, bogus data assimilation, parameterization


1 Introduction

Typhoons are one of the most severe high-impact weather systems in China and in other vulnerable coastal areas. A numerical weather model (NWM) is one of the best tools to study and predict these high-impact weather systems. However, there are two kinds of problems with NWM: Its abilities and initial conditions (ICs). These problems are due to the lack of thorough knowledge of the typhoon system itself, including its inner dynamic and thermodynamic mechanisms, its interactions between atmosphere and sea and with circumambient weather systems. As a result, the NWM cannot accurately describe the structure and movement of a typhoon. Furthermore, with the limited horizontal and vertical resolution of the model, many complicated processes must be simplified with parameterizations. For example, in the Fifth-Generation NCAR/Penn State Mesoscale Model (MM5, Grell et al., 1994), there are three major kinds of parameterized physical processes (cumulus convection, cloud microphysics, and planetary boundary layer (PBL)), each of which has a few options with different impacts on typhoon simulation. Deng et al. (2005) investigated the effect of PBL schemes on the structure of typhoons, while Hao et al. (2007) compared five cumulus parameterization schemes on typhoon track ensemble prediction. Ha et al. (2009) also studied the impact on typhoon track by cumulus together with microphysics parameterization schemes. Few studies are focused on the impact of parameterizations on the intensity of typhoons. In this paper, as a pre-study, we investigated the ability of these parameterization schemes to model the intensity and the track of a typhoon, then we used the results in a new data assimilation system.

Initial conditions (ICs) are another challenge for NWM, especially for typhoons, because they develop and spend most of their lifespan over the ocean, where there are few conventional observations (Wang et al., 2000). From a few observed parameters, Fujita (1952) gave a conceptual typhoon sea surface pressure distribution (bogus), but how to generate a more objective vortex with dynamic and physical consistency is a problem. Instead of planting the bogus directly, Zou and Xiao (2000) and Xiao et al. (2000) developed an adjoint-based four-dimensional variational (4-DVar) bogus data assimilation system (BDA) that can assimilate this bogus pressure by the model’s constraints and subsequently improve the model’s ICs. Because the cost function is minimized by running a tangential linear model and its adjoint model iteratively, there are some associated disadvantages, including tangential linear approximation, adjoint model coding, and enormous computing cost. In this study, we replace the inconvenient minimization process with a new method developed by Wang et al. (2010). This model can assimilate bogus data and many other observation data by dimension-reduced space projection (DRP). Thus, we name the model DRP-BDA.

2 Brief introduction to DRP-4-DVar and DRP-BDA

By combining the advantages of the Ensemble Kalman Filter (EnKF) and the classic 4-DVar, Wang et al. (2010) introduced a new method of dimension-reduced projection 4-DVar (DRP-4-DVar). This method projects analysis variables from the model space to the sample space represented by a group of base vectors, which are constructed with the ensemble members. Because the freedom of the
sample space is very small ($10^1$–$10^2$), the optimum solution of the cost function can be directly calculated in the sample space and then projected back onto the model space to obtain the optimal analysis field. Thus, the DRP-4-DVar is a highly economical approach compared with the classic adjoint-based 4-DVar. The new approach shares some merits with EnKF. For example, it estimates error covariance from ensemble members from the fully nonlinear forecast model, it obtains solutions in a reduced space, and it is model-independent and thus can be easily applied to any other model without substantial programming work. In addition, as a 4-DVar, it can assimilate all observations during the assimilation window simultaneously. This new approach has been verified and applied in a couple of models (Liu and Wang, 2009; Wang et al., 2010; Liu et al., 2010). The assimilated data include model variables, rain data, and satellite observations.

In this study, we apply the DRP-4-DVar to MM5 to assimilate bogus typhoon pressure. The flow chart of DRP-BDA is depicted in Fig. 1. Compared with adjoint-based 4-DVar BDA, the greatest difference is the minimization; the iterations of the tangential linear model and its adjoint model are replaced by the dimension-reduced projection, which is in low-dimensional space and can be resolved directly. Another difference is that there is a localization process in DRP-BDA. Because the ensemble is composed of far fewer members than both the number of observation data and the degrees of freedom of the model variables, it leads to spurious correlations between observation locations and model grids. As noted by Wang et al. (2010), the quality of ensemble members significantly affects the performance of DRP-4-DVar. Instead of the method attempted by Zhao and Wang (2010), who used a 3-DVar system to produce initial perturbation samples that showed efficiency in heavy rain prediction, we attempt to improve the quality of the ensemble members in two aspects: to make more members and to increase the spread of the ensemble. Both of these goals can be achieved using NWM parameterization combination.

3 Experimental design and sample preparation

The typhoon we chose is 200813 (Sinlaku). This typhoon formed on 7 September 2008, in the northeast of Manila, and was upgraded to a tropical depression next day. On 10 September, Sinlaku had a 965 hPa center pressure ($P_c$), and it continued to intensify. On 13 September, Sinlaku landed on Taiwan, China, bringing strong winds and heavy rain. The storm also dumped heavy rain on the eastern coast of China, then quickly moved northeast. (From http://agora.ex.nii.ac.jp/digital-typhoon/summary/wnp/s/200813.html.en)

We simulated the storm from 0000UTC 10 to 0000 UTC 14 September (00–96 hours, henceforth). The model we used is MM5 V3.7.3, and it was configured with two nested domains. The coarse domain size is 110×90, with a grid size of 60 km and a time step of three minutes. The fine domain is located at nearly the center area of the coarse one, with a nest size of 163×142, a grid size of 20 km, and a one-minute time step. All of the following results are from the fine domain. The vertical levels are 29 and up to 100 hPa. The model background, bilateral and lower boundary fields are from a 1°×1° National Centers for Environmental Prediction (NCEP) Final Analyses (FNL) data set. The observation datum is a bogus sea level pressure from the Fujita formula, with a center pressure of 965 hPa. The observation is used five times in both domains, with a time interval of 30 minutes; thus, the assimilation window is 0 hour to 2 hours.

The basic technique of sampling is depicted by Zhao and Wang (2010). However, instead of using the same historical forecast model initiated from a few different times, we run a number of different models from the same time. The number and the difference of the models are determined by the combination of three kinds of model parameterization schemes mentioned previously. For this study, we configure and compile all possible options and their combinations, and we find that there are approximately 140 combinations that can be run successfully, and each of the model outputs can produce 190 samples. With the purpose of typhoon simulation, we assess the quality of samples by the $P_c$. From this point of view, we found that the cumulus scheme dominated the overall trend of $P_c$. In this background, the other two parameters exhibited corresponding diversities, i.e., a large spread in a deeper typhoon and vice versa. We select the Grell and new Kain-Fritsch (KF2) groups (each group has more than 2000 samples) as DRP ensemble samples, which represent the moderate and larger intensities as well as the spread.

After the samples and bogus observations are prepared, we begin to run DRP-BDA. From the printout of the ex-
Experiment (not given) with the new sampling method, an average of 5.5% of the samples pass the quality control, while the original method obtains only 3%. The cost function decrease is also improved (50% vs. 45%). Finally, we obtain an optimal model IC. Once again, to eliminate the uncertainty of model parameterizations, we run a couple of models from the optimal IC with relevant parameters. It is worth noting that compared with the DRP-BDA process itself, which takes less than 10 minutes on a 2.66 GHz Central Processing Unit, the sample preparation process (i.e., historical-forecast model integration) is somewhat time-consuming. However, this problem can be ameliorated with a computer cluster in an operational center; it only needs to run one time, and all the samples can be reused in other typhoon cases.

4 Results

Figure 2 shows the partial results before and after DRP-BDA, the typhoon $P_c$ evolvement (Fig. 2a), and the center moving track (Figs. 2b and 2c) based on the Grell cumulus convection scheme. There are two bundles in Fig. 1a: all ensemble members (i.e., the control runs) start from 998 hPa, while all analyzed runs start from 970 hPa at 0 hour, and in the following 48 hours to 60 hours, the analyzed runs can retain the typhoon’s intensity. Comparing Fig. 2b with Fig. 2c, after DRP-BDA, the strengthened typhoon movements show a more systematic northwest trend, while the weaker samples meander in the first half of the period, then move north to northeast in the second half. Quantitatively, the mean track error of the first 36 hours is reduced from 97 km and 42 km after DRP assimilation. It is necessary to note that all the simulated typhoons move faster than the real one and that the track error grows quickly in the second half of the stage.

The improvement achieved by DRP-BDA can be seen in experiments based on better samples. Figure 3 shows the same items except for the cumulus convection scheme KF2. It can be seen that most of the samples show adequate ability to represent typhoon intensity, from 998 hPa to an astonishing 940 hPa, and after DRP assimilation, we still can gain an additional 15 hPa to 20 hPa pressure decrease in the first 36 hours. Consequently, the trend of improvement on tracking in this stage is also remarkable; instead of a tangle in the first hours, the optimized typhoons move toward the northeast systematically, then to the northwest, just as the best track. The modeled typhoons maintain the trend to the ending hours, while the control runs become divaricated. Studying the track error, compared to Grell scheme, the mean error of the KF2 scheme improved slightly from 64 km to 61 km; the main reason for this improvement is that the average deeper typhoon moves faster, and the error becomes greater even though the trends are more systematic.

To determine what other improvements are brought by DRP-BDA, we compare the typhoon structure before and after assimilation. Figures 4a and 4b show the cross-section of zonal temperature disturbance at 0 hour (analysis) and after 24 hours of integration. It can be seen, after assimilating the sea surface pressure, that we can acquire and maintain a moderate warm core structure ($4^\circ\text{C to } 6^\circ\text{C}$), while in an adjoint-based BDA experiment (with a different model configuration due to the limitation of the adjoint model), the initial warm core is as high as $14^\circ\text{C}$ near 900 hPa, but it disappears after a few hours of integration (Wang (2010), figure not given). Figure 4c shows the analysis increment of meridional wind speed near the typhoon center. It can be observed that DRP-BDA increases the wind dramatically (original north wind 20 m s$^{-1}$ and south wind 24 m s$^{-1}$; the increment is 16 m s$^{-1}$ and 40 m s$^{-1}$, respectively), and it maintains the strong wind in the forecasting hours. At 24 hours, the north and south winds still remain at 36 m s$^{-1}$ and 52 m s$^{-1}$, respectively.
In the adjoint-based BDA, the increment of wind speed is negligible at 0 hour. After the model integration, the wind speed starts to strengthen, and at 24 hours, the meridional wind speed is increased to 36 m s\(^{-1}\). These results imply that DRP-BDA can create more dynamic typhoons than the adjoint-based BDA.

The improvement of tracking in DRP-BDA can be measured by the deep layer mean (DLM, Velden and Leslie, 1991; Franklin et al., 1996), which is correlated with the typhoon steering flow and created by mass-weighting mandatory-level wind. Before DRP-BDA, the DLM of the initial hour is 3.5 m s\(^{-1}\), and the moving direction is
340°. After the assimilation, the DLM is 3.1 m s\(^{-1}\) at 335°, while the observed movement is 2.3 m s\(^{-1}\) at 335°. In the following hours, the DLM-optimized runs are still more well organized than the control runs; in other words, the typhoon moves more systematically after assimilation. There is still a problem that deserves further study: The typhoon of the control run and the optimized run moves faster than the real one.

5 Summary and discussion

In this study, we introduce a new bogus data assimilation system based on DRP-4-DVar, which can resolve the cost function directly in dimension-reduced space. The base vectors of the low-dimensional space are constructed with the ensemble members, and the quality of ensemble members significantly affect the DRP-4-DVar performance. Instead of few historical forecasts, we run a number of MM5 models with three major parameterization combinations, and we create two groups of samples with different spreads and similarities. After DRP-BDA, the results show that the simulated typhoon center pressure can be deepened by more than 30 hPa and can last as long as 60 hours in intensity. Additionally, the tracks are more systematic than those of the control runs. Regarding the typhoon structure, the wind is enhanced dramatically, while the warm core is moderate. Based on more qualified samples, the improvements of the typhoon’s intensity and tracks are also significant.

Encouraged by this case study, we will continue to apply DRP-BDA to more typhoon cases. Other valuable typhoon observations, e.g., dropwindsonde, satellite and radar data will be used in the future.

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