Initializing a Hurricane Vortex with an Ensemble Kalman Filter

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1. Introduction

Despite steady improvements during the last several decades, both track and intensity forecasts for hurricanes still exhibit significant errors. Initializing a hurricane vortex with realistic structures in the correct location and with the correct storm motion is crucial to accurate forecasts.

Currently, many operational centers rely on sophisticated hurricane bogussing and relocation schemes. Due to the inconsistency among different model fields and between the vortices and their environment, the initial hurricane vortices are not always in good balance, especially when the analysis and the forecast are preformed using two different models. Such imbalances result in spurious spin-up processes which may lead to substantial forecast errors.

The ensemble Kalman filter (EnKF) uses exactly the same model for both analysis and forecast. The flow-dependent error covariances which are directly calculated from the ensemble enable the EnKF analysis to generate physically consistent increments. The spin-up problem can then be significantly reduced.

2. EnKF scheme and observations

An ensemble adjustment Kalman filter (Anderson 2001) implemented in the Data Assimilation Research Testbed (DART) system and the Weather Research and Forecasting (WRF) model are used in this study.

With the EnKF, the hurricane position and intensity observations can be directly assimilated (Chen and Snyder, 2006). Assimilated observations include real-time hurricane center positions and minimum sea level pressure estimates from the National Hurricane Center (NHC) advisories, and cloud-track satellite winds. Only 3% to 5% of the available satellite wind observations are assimilated. The forward, or observation, operator for the hurricane position is simply an algorithm that returns the grid-point location of the minimum sea level pressure given the model fields.

The observational errors for the satellite winds are set to be a constant of 5 m s^{-1}. The center position estimates are assumed to have errors of 0.3 degree (about 30 km). The errors of the minimum sea level pressures are set to be 5 hPa (except 30 hPa in Ivan 2004 experiment).

3. Real-case experiments

We performed assimilation and forecast experiments for four Atlantic hurricanes (Ivan in 2004, Katrina, Ophelia and Rita in 2005), and one Pacific typhoon (Dujuan 2003). For these experiments, the WRF model employs 36-km or 45-km horizontal resolution and 35 terrain-following vertical levels. Model physics includes the Kain-Fritsch cumulus parameterization, the WRF single-moment 3-class microphysics scheme and the Yonsei University (YSU) boundary layer scheme. The ensemble initial conditions and boundary conditions are generated by randomly perturbing Global Forecast System (GFS) analysis with spatially correlated, Gaussian noise. The spatial and multivariate covariances of this noise are provided by the background covariance model of WRF-3DVAR. The ensemble members are advanced forward and are regularly stopped at the assimilation frequency when the available observations are assimilated. Table 1 lists the experiment configurations.

a. EnKF analysis increments

Usually the GFS analysis or the background forecast from GFS analysis contains, if any, only a weak vortex, and sometimes the vortex is misplaced in space. The vortex center displacement can be corrected by assimilating their center position observations. Chen and Snyder (2006) show in an idealized, barotropic problem that when the position error is small and Gaussian, the EnKF approximates an optimal analysis and moves the vortex toward its observed location. On the other hand, assimilating the minimum sea-level pressure can adjust the intensity of a hurricane vortex.

As an example, Fig. 1 shows the vertical cross-sections of the wind and potential temperature increments across the center of Hurricane Rita 2005 at 23 UTC 23 September, 2005 after assimilating its center position and intensity. At this time, the forecasted center position is already very close to the observation, and the increments are mainly caused by assimilating its intensity observation (973 hPa). The increments in u-wind component show intensification of the cyclonic rotation, meanwhile the in-up-out secondary circulation is enhanced. Correspondingly, the potential temperature increments exhibit warm core structure. This is in the right sense to intensify Rita. Consequently, the minimum sea-level pressure drops from 989 hPa to 987 hPa.

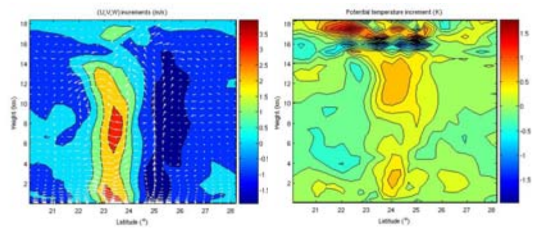

Figure 1. Vertical cross sections of (a) wind (u component in shading, v and w components in vector) and (b) potential temperature increments for Hurricane Rita (2005), valid at 2005-09-20-23Z.

b. Comparison of track forecasts

At the end of the assimilation time window, we use the ensemble mean analysis to initialize a deterministic forecast, which will be compared against the cold-start forecast initialized from GFS (AVN) analyses. Figure 2 compares track forecasts with the best track analyses for all 5 storms.

The cold-start forecast of Typhoon Dujuan (2003) from 00 UTC August 31, 2003 indicates landfall in Taiwan on September 01, 2003. The EnKF forecast follows closely to the real track and correctly predicts the landfall location near Hong Kong (Fig. 2a).

Figure 2b shows that both cold-start track forecasts of Hurricane Ivan (2004) from 00 UTC September 12 and 13, 2004 have large westward displacement from the analyzed track in the Gulf. By assimilating vortex position, vortex intensity and satellite winds, the EnKF decreases the displacement of the forecast tracks. Ivan was a Category 4-5 storm during the assimilation time. The model resolution of 36-km can not resolve such strong storm. We choose a large observational error of 30 hPa for the minimum sea-level pressure to partially compensate the model bias.

The track forecasts of Hurricane Katrina (2005) are very sensitive to the initial conditions and boundary conditions. The forecast initialized from GFS analysis at 12 UTC August 25, 2005 has much smaller errors comparing to the forecast beginning from 12-h later GFS analysis at 00 UTC August 26. However both tracks turn northward too early. In contrast, the EnKF analysis yields a nearly perfect track forecast which accurately predicts landfall in New Orleans, Louisiana 4 days in advance (Fig. 2c).

Hurricane Ophelia (2005) is a weak Category 1 hurricane. It slowly made a clock-wise loop on September 11-12, 2005 as shown in Fig. 2d. Even though none of the forecasts captures this loop, the EnKF analysis still gives smaller track forecast errors comparing to the GFS cold-start beginning at the same time (00 UTC September 10, 2005).

Figure 2e again demonstrates the positive impact of the EnKF analysis on the track forecast of Hurricane Rita (2005). The track predicted from the EnKF analysis surpasses that of the GFS analysis for more than 3 days.

In general, the forecasted intensities are weaker than the best track estimates as expected given relatively coarse model resolutions. Nevertheless, the EnKF analyses result in better intensity forecasts comparing to the GFS analysis (not shown).

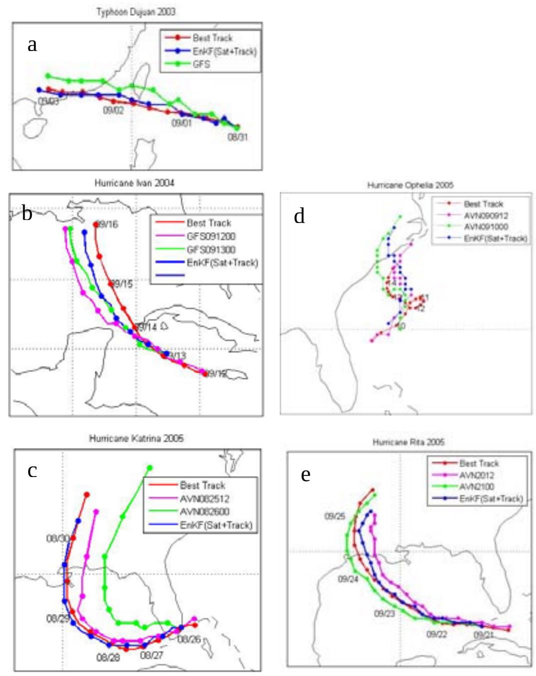

Figure 2. Comparisons of track forecasts initialized from the EnKF analysis (blue) and GFS analysis (green and magenta) for (a) Typhoon Dujuan 2003, (b) Hurricane Ivan 2004, (c) Hurricane Katrina 2005, (d) Hurricane Ophelia 2005, and (e) Hurricane Rita 2005. The best tracks are plotted in red curves.

c. Vortex spin-up

By frequently assimilating hurricane positions and intensities during a period of time, the EnKF can generate a hurricane vortex with reasonable intensity moving along its right track. More importantly, the vortex develops dynamically consistent and balanced structures so that the spurious vortex spin-up process can be well reduced.

To demonstrate the smooth development of the vortex from the EnKF analysis, Fig. 3 compares the time evolutions of the domain-averaged absolute value of the surface pressure tendency and the domain-total precipitation in the first 24-h forecasts initialized from the EnKF and GFS analyses at 00 UTC September 13, 2004 for Hurricane Ivan. The domain-averaged surface pressure tendency, an indicator of the model generated artificial fast moving gravity waves, is one time larger in the forecast from the GFS analysis than that from the EnKF analysis. The single point value of this tendency at the beginning of the forecast from the GFS analysis can be even one order larger in the hurricane core region (not shown). They decay quickly to a constant level of about 50 Pa/h after 12 hours. Unlike the cold-start from GFS analysis in which there are no initial vertical motions or hydrometers, the EnKF analysis updates the vertical motion and hydrometeor fields consistently with other dynamic and thermodynamic fields. The “burst” in the initial precipitation and consequently the shocks in diabatic heating are suppressed in the EnKF forecast.

4. Summary

A new EnKF-based hurricane initialization scheme has been developed and implemented in the WRF/DART framework. In this study, only hurricane center locations and intensities and a small subset of the available satellite winds are assimilated. The EnKF analysis produces dynamically consistent vortex structures, which lead to smooth evolution of the vortex in the subsequent forecast. In all five hurricane/typhoon real-case experiments, the track forecasts initialized using the new EnKF scheme show significant improvements comparing to the forecasts initialized from the GFS analysis.

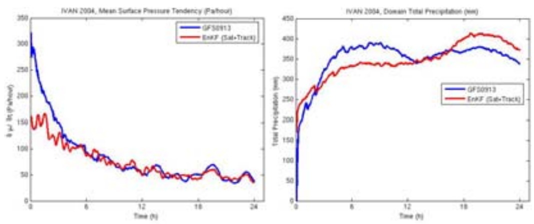

Figure 3. The first 24-h time evolution of (a) the domain-averaged absolute value of the surface pressure tendency (in Pa/hour) and (b) the domain-total precipitation (in mm) in the forecasts initialized from the GFS analysis (blue) and the EnKF analysis (red) for Hurricane Ivan (2004) starting from 00 UTC 13 September, 2004.

References

Anderson, J., 2001: An ensemble adjustment Kalman filter for data assimilation. *Mon. Wea. Rev.*, **129**, 2884-2903.

Chen, Y., and C. Snyder, 2006: Assimilating vortex position with an ensemble Kalman filter. *Mon. Wea. Rev.*, in review.

Table 1. Experiment configurations

Storm name	Resolution	Ensemble size	Assimilation time window	Assimilation frequency
Dujuan 2003	45 km	26	2003.08.30.00Z -- 08.31.00Z	3 hours
Ivan 2004	36 km	28	2004.09.12.00Z -- 09.13.00Z	3 hours
Katrina 2005	36 km	26	2005.08.25.12Z -- 08.26.00Z	1 hour
Ophelia 2005	36 km	26	2005.09.09.12Z – 09.10.00Z	1 hour
Rita 2005	36 km	26	2005.09.20.12Z -- 09.21.00Z	1 hour