11.8 TROPICAL CYCLONE MODELING IN A PROBABILISTIC FRAMEWORK

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1. INTRODUCTION

The emergence of ensemble data assimilation methods such as the ensemble Kalman filter (EnKF) (e.g. Evensen, 2003, hereafter E03) brings with it the possibility of casting the more general problem of numerical weather prediction (NWP) in a probabilistic framework. Since it may be demonstrated that any single model forecast is only one of infinitely many possible realizations of a random process, the nature of which depends strongly on the realizations of other random variables (e.g. observations), it is important to focus not only on the forecast itself but also on the associated forecast error. Ensemble methods are ideally suited to accomplishing this task, as error statistics may easily be estimated from the ensemble of forecasts. Section 2 details an application of the EnKF to probabilistic tropical cyclone prediction through the vehicle of an observing system simulation experiment (OSSE), including a brief description of the spaceborne Doppler radar that constitutes the motivation for this experiment. Section 3 gives a discussion of the results obtained, and conclusions are presented in section 4.

2. OSSE METHODOLOGY

An OSSE is conducted to determine the impact of remotely sensed hyrometeor vertical velocity , w_h, on a simulation of Atlantic hurricane Beta (2005) conducted with the University of Wisconsin Nonhyrostatic Modeling System (UW-NMS) (Tripoli, 1992). These data are of the type to be delivered by the NEXRAD-In-Space (NIS) instrument (Im and Durden, 2005). NIS will be a 35-GHz Doppler radar in geosynchronous orbit over the Atlantic tropics, allowing hourly observations of w_h and radar reflectivity, Z, with horizontal resolutions of 12-14km and a vertical resolution of 300m. NIS will allow, for the first time, insight into the vertical motion fields of developing and intensifying tropical cyclones. It is anticipated that NIS will help elucidate processes involved in tropical cyclone formation and evolution as well as prove beneficial to operational NWP.

To test the latter assertion, as well as to demonstrate the possibilities of probabilistic NWP, a Truth simulation (TR) is first conducted in order to produce synthetic observations and to provide a standard for computing forecast and analysis errors. The simulation is initialized from the high-resolution GFS analysis at 12Z 28 October, approximately 24 hours before Beta attained hurricane strength. Two grids are employed, an outer grid with 52-km resolution and 100 gridpoints in x and y, and an inner grid with 13-km resolution and 60 gridpoints in x and y. Vertical discretization is accomplished for both grids with 60 gridpoints and 300m resolution. Boundary conditions are provided by the GFS high-resolution analyses, SST is provided by NOAA weekly optimum interpolation, and the model is integrated for 60 hours with a coarse-grid timestep of 120 s. The track and intensity of the model cyclone (TR) are compared with those of the 6-hourly TPC (TPC) advisories in figure 1. Despite the rather coarse resolution of the inner grid, the track and especially the intensity of the model cyclone agree rather well with observations. Though not of paramount importance – the TR simulation will be the basis for judging the success of the assimilation experiment described below – it does demonstrate that the UW-NMS handles the evolution of Beta well.

The NIS instrument is anticipated to have a minimum detectable signal of 5 dBZ, and so observations of w_h are computed at those points in the inner grid where the simulated reflectivity factor meets or exceeds this threshold. This results in an average of 25,000 observations available at each observing time. The initial condition for the assimilation experiments is a 6-hour GFS forecast valid at 12Z 29 October. A 25-member ensemble is generated by adding to this forecast correlated Gaussian random noise, as in E03, with a decorrelation scale of 124 km (i.e. 8 hoirzontal gridpoints). The standard deviation of

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the noise is 3 m/s for u and v, and 3 K for the ice-water liquid potential temperature θ_{il} (the prognostic thermodynamic variable in this model). The resulting ensemble is then integrated forward for 12 hours to allow for adjustment and spin-up and to allow correlations to develop among the various model fields. Assimilation of w_h commences at 00Z 30 October and continues each hour thereafter with assumed uncorrelated observation errors of 1 m/s. The resulting analysis fields are then compared to those from the TR simulation to adjudge the impact of the data.

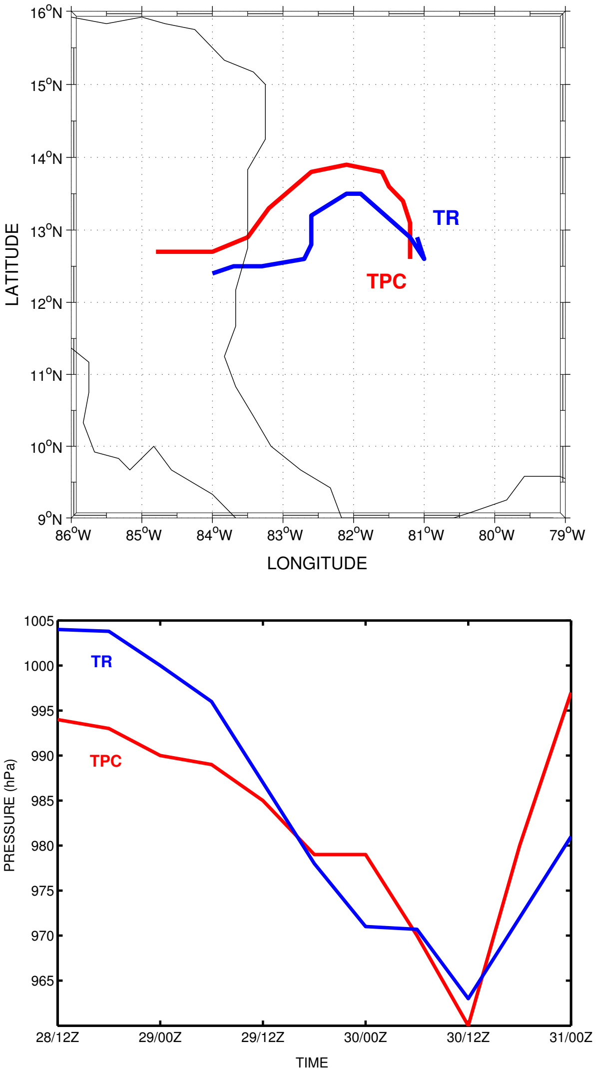

Figure 1. Top: track comparison of model cyclone (blue) and TPC advisory positions (red) for the period 12Z 28 October to 00Z 31 October. Bottom: minimum central pressure for the model simulation and from TPC advisories for the same time period.

3. RESULTS

First, it will be useful to consider the errors present at the beginning of the assimilation period but before any filtering begins. Figure 2 shows ensemble-mean (EM) errors for windspeed (knots) and vertical velocity (m/s) at 3km for the time 00Z 30 October. Several things are evident: first, the errors are primarily of magnitude (and not phase), indicating that the EM cyclone track is essentially coincident with the TR cyclone track; second, the EM generally understimates both windspeed and vertical velocity, which is unsurprising given the nature of the averaging process and the relatively small ensemble size.

However, after only 3 hours, the EnKF analysis improves dramatically, as can be seen by considering the errors plotted for windspeed and vertical velocity in figure 3 for the time 03Z 30 October. There is considerable reduction of the errors in the eyewall region of the cyclone, although the spiral banding feature several hundred kilometers north of the center is still somewhat poorly resolved. This is essentially due to this feature being absent or having a substantially weaker representation among the ensemble members. A larger ensemble and a longer spin-up would likely improve upon this result, giving such peripheral structure time to evolve.

Another weakness in the analysis can be identified near 12°N, 85°W and is associated with a developing convective burst soutwest of the center in the TR simulation. The analysis responds sluggishly to the observations marking this feature, largely because after 3 assimilation cycles a considerable degree of the ensemble spread in the vicinity of the hurricane core has been depleted. There are several methods currently used to mitigate such contraction of the ensemble, among them covariance inflation and data weighting. Neither of these techniques is entirely satisfactory, and so the authors are currently developing a new method based on resampling.

Finally, to emphasize the role of the EnKF in probabilistically treating the cooperative filtering / NWP process, a comparison of actual surface rainwater mxing ratio errors and those predicted by the ensemble spread are shown in figure 4. There is good correspondence between the two, showing the EnKF can produce reasonable 2nd moment estimates to complement its 1st moment estimate. Similar results hold for other fields.

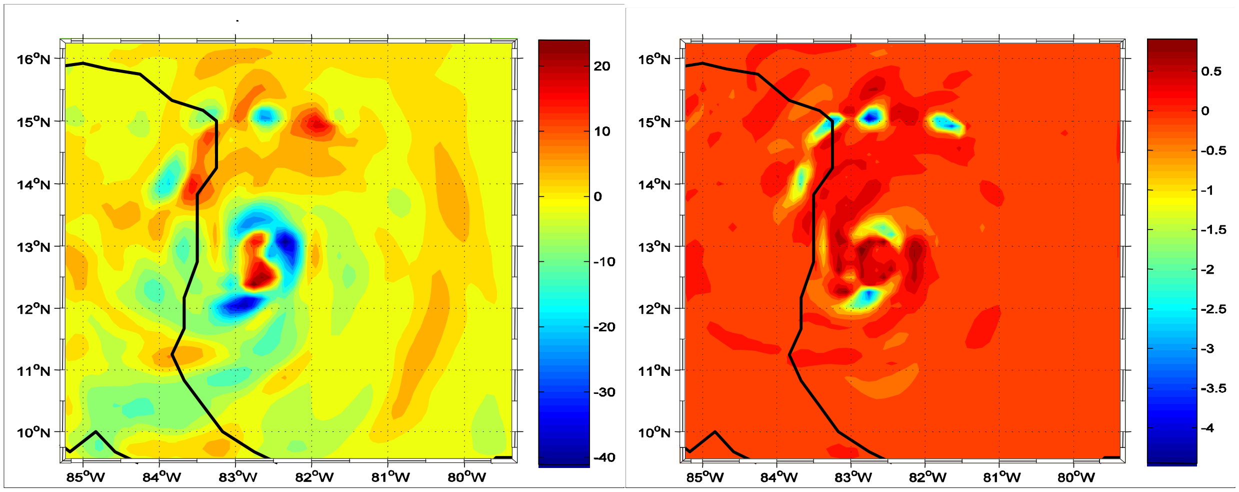

Figure 2. Forecast errors at 3km for 00Z 30 October. Right: windspeed (knots). Left: w (m/s).

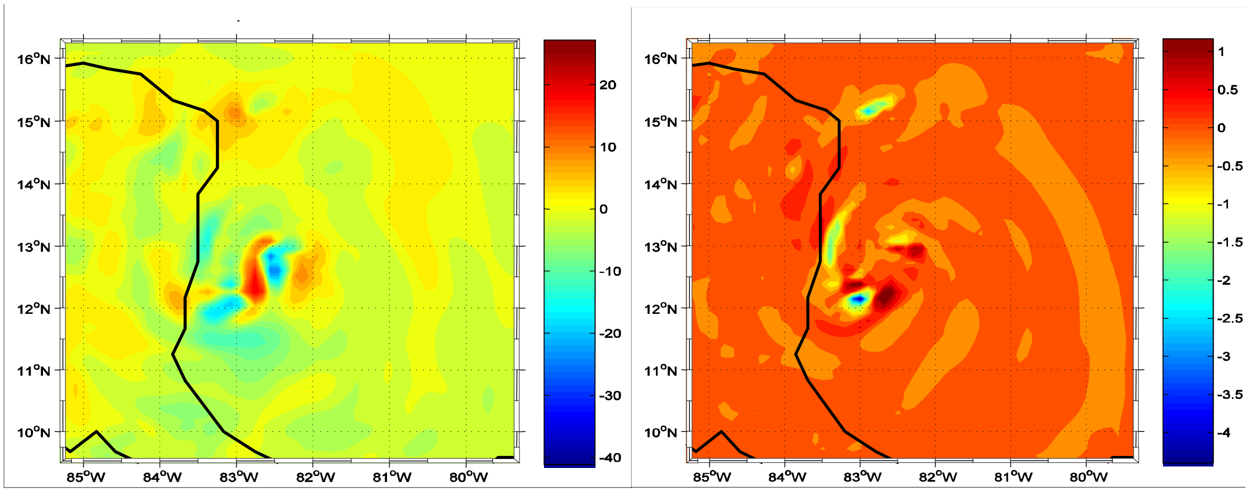

Figure 3. Analysis errors at 3km for 03Z 30 October. Right: windspeed (knots). Left: w (m/s).

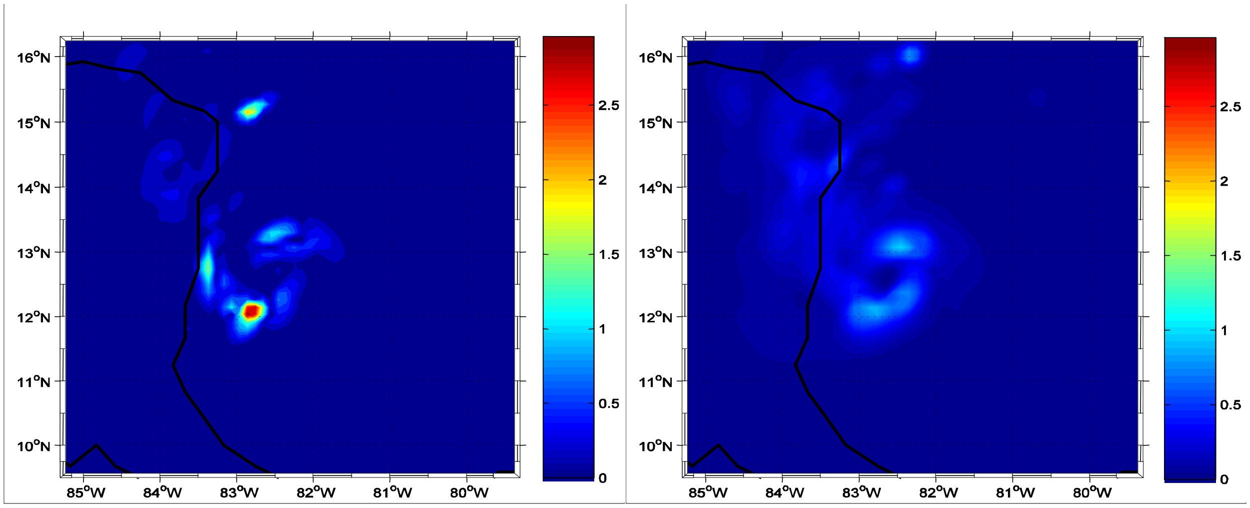

Figure 4. True (right) and predicted (left) rainwater mixing ratio (g/kg) errors for 03Z 30 October.

4. CONCLUSIONS

The aptness of the ensemble Kalman filter for convective-scale, i.e. isolated supercell, data assimilation has been demonstrated by numerous authors (e.g. Lewis and Tripoli, 2006), but comparitively less work has been done on dynamically stiff phenomena such as the tropical cyclone case presented here. That the EnKF is capable of producing accurate analyses with a relatively small ensemble in this context is encouraging, especially so taking into account the EnKF's native ability to provide on-line estimates of analysis error. This, in essence, makes the EnKF a fully probabilistic tool for data assimilation (under the assumption, of course, that the atmospheric state pdf is Gaussian and thus completely described by its 1st and 2nd moments – mean and covariance, respectively). This is important when it is remembered that any forecast is but one possible realization of the atmospheric state, and therefore having an estimate not only of the state itself (the ensemble mean) but also of the associated error (the ensemble (co)variance) is not only highly desirable but indispensable.

The authors are currently in the process of conducting a series of more thorough experiments, including several cases of rapid intensity change and cyclogenesis, which should more fully delineate the EnKF's role in guiding NWP in the broader range of processes that span the tropical cyclone problem. Additional experments designed to gauge the impact of assimilating other observation types and the influence of a more realistic treatment of observation error are also in progress, as are experiments more fully exploiting the probabilistic nature of the ensemble method. The results are forthcoming.

5. REFERENCES

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