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# Impact of Dropwindsonde Data on the Track Forecasts of a Tropical Cyclone: An Observing-Systems Simulation Experiment Study

**Seon K. Park**[1], **Da-Lin Zhang**[2] **and Hyun Hee Kim**[1]

[1]*Severe Storm Research Center and Department of Environmental Science and Engineering, Ewha Womans University, Seoul, Korea*
[2]*Department of Atmospheric and Oceanic Science, University of Maryland, College Park, Maryland, U.S.A.*

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## Abstract

In this study, the model initial uncertainties associated with the track forecast of Hurricane Bonnie (1998) is examined through a series of observing-systems simulation experiments (OSSEs) with the Penn State University-National Center for Atmospheric Research mesoscale model (i.e., MM5). Analysis soundings with varying densities and configurations are used to mimic the inclusion of dropwindsonde data in the model initial conditions. Results show that increasing the soundings around the storm center improves the track forecasts. Enhanced observations in any quadrant of the storm would result in better track forecasts, but the forecast improvement is more pronounced when more soundings are added to a region of stronger winds. The results indicate that proper design of the dropwindsonde distribution and density is crucial to the improvement of the track forecasts of tropical cyclones.

**Key words:** Dropwindsonde, data impact, data assimilation, tropical cyclone

## 1. Introduction

The past two decades have witnessed steady improvements (about 1% per year) in the track forecasts of tropical cyclones (TCs), which reduced significantly the loss of life and property damage over the coastal regions (see McAdie and Lawrence, 2000; Aberson, 2001; Elsberry, 2002). These improvements have been achieved by reducing the numerical weather prediction (NWP) model deficiencies (Lorenz, 1990; Reynolds *et al.*, 1994; Zhu *et al.*, 1996), but primarily by taking advantage of more available observations from satellite, radar and instrumented aircraft, and by using newly developed algorithms to incorporate these data into NWP models (e.g., Burpee *et al.,* 1984; Franklin and DeMaria, 1992; Velden *et al.,* 1992; Leslie *et al.,* 1998).

Among the various observing platforms, the Global Positioning System (GPS) dropwindsonde, frequently called a dropsonde, is a widely-used instrument for collecting meteorological data inside TCs. This cylindrical instrument is ~7 cm in diameter, 40 cm in length, and ~0.4 kg in weight. The instrument package, including a parachute, is deployed from the aircraft and falls through the storm measuring temperature, pressure, winds, and humidity at every half-second (see NCAR, cited 2008 for the details).

The dropwindsondes appear to provide the efficient information for improving the TC track forecasts. For instance, Burpee *et al.* (1996) indicated that the impact of dropwindsonde observations on the track forecast improvement (16-30% for 12-60 h forecasts) was as large as the accumulated improvement in operational forecasts achieved over the 22-year period from 1970 to 1991. Aberson and Franklin (1999) demonstrated that the dropwindsonde observations improved the mean track fore-

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Corresponding Author: Prof. Seon K. Park, Department of Environmental Science and Engineering, Ewha Womans University, Seoul, 120-750, Korea.
Phone : +82-2-3277-3331, Fax : +82-2-3277-3275
E-mail : spark@ewha.ac.kr

cast of the Geophysical Fluid Dynamics Laboratory (GFDL) TC model by as much as 32% and the intensity forecast by as much as 20% within 48 h of projected landfall.

Despite the above-mentioned remarkable progress, our ability to accurately predict the TC tracks a few days in advance, especially near landfall, is still very limited due to the fact that TCs spend most of their lifetime over vast tropical oceans, where little data are available. While some reconnaissance flights could provide much useful data for NWP models, it is not possible to obtain high-quality, high-resolution observations over sufficient large areas; namely, an area coverage with a radius of 1,500 km from the TC center is necessary for a 2-3 day forecast. As a result, some adaptive observing strategies have recently been examined for deploying dropwindsondes in dynamically sensitive, data-sparse regions (Zhang and Krishnamurti, 2000; Aberson, 2003).

How to effectively incorporate different observations into NWP models is another challenging task. Using a quasi-geostrophic and three-dimensional variational data assimilation system, Morss and Emanuel (2002) found that adding observations in some cases may degrade the quality of analyses and forecasts, even with perfect observations and a perfect forecast model. This is inherently caused by deficiencies in the assimilation system, lacking knowledge of error statistics, and nonlinear error growth in the assimilation-forecast system. However, they also identified some situations in which adding observations improves analyses and forecasts: i.e., when added observations (a) decrease global-average analysis; and (b) occur at the locations where initial-condition errors are large and where the ensemble spread has less vertical structures. The results imply that the impact of adding observations on the TC track forecasts depends strongly on the environmental flows as well as the dynamics of TCs.

Thus, the purpose of the present study is to investigate the impact of dropwindsonde data on the track forecasts of TCs in terms of different densities and configurations of the measurements through a series of observing-systems simulation experiments (OSSEs). This will be done by examining the model initial uncertainties related to the track forecasts of Hurricane Bonnie (1998) using the fifth generation of the Penn State University/NCAR nonhydrostatic mesoscale model (i.e., MM5). Although there have been numerous OSSE studies in the literature to examine the impact of different measurement plans on the prediction of large-scale and mesoscale weather systems with both general circulation models and NWP models (e.g., Arnold and Dey, 1986; Kuo *et al.*, 1987; Zou *et al.*, 1995), few OSSE studies have been performed for the TC systems that are driven by latent heat release.

The present study is organized as follows. The next section provides a brief description of the case, including its associated track forecasts, and the fundamental model options used for this study. Section 3 presents the logics of OSSEs associated with Bonnie and describes the design of OSSEs. Section 4 shows the simulated tracks from various OSSEs. A summary and concluding remarks are given in the final section.

## 2. Case and Model Description

Hurricane Bonnie originated from a tropical depression at 1200 UTC 19 August 1998; it became a named tropical storm at 1200 UTC 20 August and reached a hurricane intensity around 0000 UTC 22 August (see Zhu *et al.*, 2004). The reconnaissance missions of the US Air Force and NOAA obtained the maximum winds of roughly 60 $\mathrm{ms}^{-1}$ at 700 hPa on 25-26 August, with a minimum pressure of 954 hPa at 0000 UTC 24 August (Avila, 1998). Bonnie hit the coast of North Carolina on 27 August. It was downgraded to a tropical storm on 29 August as it turned northeastward over a colder ocean surface.

Almost all of the operational model forecasts at that time, initialized with the National Centers for Environment Prediction (NCEP) analysis on August 22, did not indicate any likelihood of the storm landfall, but predicted more than 1,200 km too far to the northeast over the sea at the end of their 5-day forecasts (see Avila, 1998). The operational models on August 23 also predicted a wide range of tracks, making the forecast a very difficult task. See Avila (1998) for a presentation of the detailed error statistics associated with various operational models.

Recently, two 5-day nested-grid, high-resolution, explicit simulation studies of Hurricane Bonnie (1998) have been published, both initialized at 0000 UTC 22 August with the NCEP analysis and integrated with the MM5 model physics (see Liu *et al.*, 1997): one by Rogers *et al.* (2003) to investigate the role of vertical wind shear in determining the distribution of rainfall, and the other by Zhu *et al.* (2004) to examine the evolution of inner-core structures and intensity changes. To obtain a reasonable simulation of the storm track, Rogers *et al.* (2003) applied a dynamical nudging algorithm to the outermost coarse-mesh domain during the first 3-day model integration. In contrast, the use of more complete observations, such as the enhanced upper-air observations over land and the Advanced Microwave Sounding Unit (AMSU) satellite measurements associated with the hurricane vortex, appears to help reproduce the hurricane track in the simulation of Zhu *et al.* (2002, 2004). It is these uncertainties in both the operational and research models that motivated us to conduct the present OSSE study associated with Hurricane Bonnie (1998), in order to gain insight into the model initial uncertainties and understand their roles in determining the track of the storm as well as the other tropical storms.

Because we are only interested in the track simulations of Bonnie, a horizontal resolution of $\Delta x = \Delta y = 54$ km for a single domain with the $(x, y)$ dimensions of 99×79 is employed. Although the horizontal resolution is quite coarse, it is aimed to show the effectiveness of additional sounding data in improving hurricane forecasts even with such a coarse grid domain. A total of 15 $\sigma$-layers in the vertical is used with higher resolution in the planetary boundary layer (PBL). The 15 half-$\sigma$ levels are defined at: 0.98, 0.94, 0.92, 0.88, 0.85, 0.81, 0.77, 0.71, 0.6, 0.55, 0.45, 0.35, 0.25, 0.15, and 0.05. The fundamental physics options in MM5 used for this study include: (a) the simultaneous use of the Grell's convective parameterization (Grell *et al.*, 1991) and an explicit simple ice microphysics scheme containing prognostic equations for cloud water (ice) and rainwater (snow) (Hsie *et al.*, 1984; Dudhia, 1989; Zhang, 1989); (b) the Blackadar PBL scheme (Zhang and Anthes, 1982); and (c) the specification of the outermost coarse-mesh lateral boundary conditions by linearly interpolating the 12-hourly analyses at according to Perkey and Kreitzberg (1976).

The model is initialized at 0000 UTC 22 August 1998, which was just a few hours prior to the significant deepening of Bonnie, and integrated for 5 days until the storm's landfall at 0000 UTC 27 August. The model starting and ending times are the same as those used by Rogers *et al.* (2003) and Zhu *et al.* (2004). Both the NCEP and the European Center for Median-range Weather Forecast (ECMWF) global analyses at the horizontal resolution of 2.5°×2.5° are used for OSSEs. See Fig. 1 for the model domain and forecasts based on the NCEP and ECMWF global analyses.

## 3. Experiment Design

During the initial numerical experimentations of the storm, we found that two 5-day simulations, initialized with respective NCEP's and ECMWF's analyses but with identical physics options, produced quite different characteristics of Bonnie in terms of

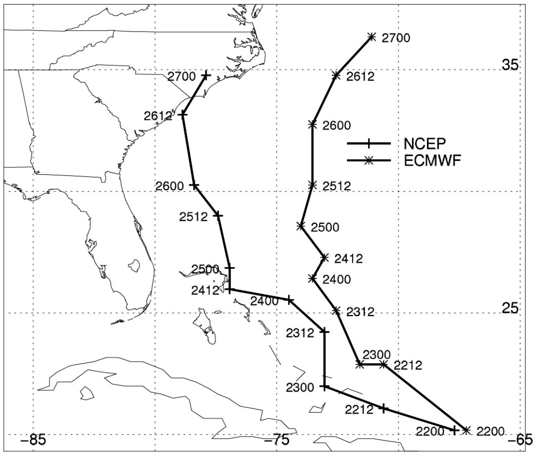

**Fig. 1.** The simulated 5-day tracks of Hurricane Bonnie (1998) initialized with the NCEP and ECMWF analyses during the period of 0000 UTC 22 - 0000 UTC 27 August 1998.

the storm track, intensity and inner-core structures. Specifically, a comparison of the simulated tracks from the two different initial conditions, as shown in Fig. 1, depicts that the simulated track using the NCEP analysis compares very favorably to the best track (see Avila, 1998), especially near the landfall, whereas the simulated Bonnie with the ECMWF analysis turns northeastward over the sea at a too early time. The difference in location at the end of the 5-day simulations is more than 700 km with quite different intensity change scenarios along the tracks. The former scenario is very similar to that obtained by Zhu *et al.* (2004) using the high grid resolution and more sophisticated physics, while the latter is similar to those predicted by most of the operational models at that time initialized with NCEP's analysis (see Avila, 1998). Thus, the two different tracks simulated from different initial conditions make this storm an ideal case to examine the initial uncertainties in the ECMWF analysis by treating the NCEP analysis as the "simulated observations" or "ground truth." The associated uncertainties could then be examined through a series of OSSEs (Arnold and Dey, 1986).

In the present study, OSSEs are conducted by taking "ground truth" soundings at selected points, just like "dropwindsondes," from NCEP's analysis at the model initial time, and then incorporating them into the control initial conditions based on the ECMWF analysis through a Cressman-type of objective analysis algorithm. The soundings taken from NCEP's analysis include temperature, moisture and horizontal winds at all the mandatory levels up to 50 hPa, noting the finding of Aberson and Franklin (1999) that dropwindsonde data at higher altitudes (e.g., about 150 hPa from NOAA's Gulfstream-IV aircraft) could provide more significant improvements in the hurricane track and intensity forecasts than those at lower altitudes (e.g., below 350 hPa from NOAA's WP-3D aircraft). In the present case, the 5-day forecast based on the ECMWF analysis with the worse storm track is defined as the control forecast. By incorporating NCEP's "dropwindsondes observations" at different points in the vicinity of Bonnie into the control initial conditions, we wish to examine how the control forecast track could be altered with different data injection strategies, and what configuration of the soundings tends to produce the smallest track error with respect to the "observed."

It is well known from the previous studies of global OSSEs that OSSEs tend to produce overly optimistic results when the same model is used to simulate "observations" or assimilate the model-generated data. This is known as the identical "twin" problem (Arnold and Dey, 1986). However, this problem appears to be less serious in mesoscale OSSE studies (e.g., Kuo *et al.*, 1987; Warner *et al.*, 1989; Zou *et al.*, 1995) due partly to the presence of more energetic small-scale disturbances and partly to the more dominant role of diabatic heating. By comparison, our approach contains little the identical "twin" problem because of the use of two different analyses to initialize a third different NWP model with different grid configurations and physics processes and because of the intense release of latent heat to drive the secondary circulations of a hurricane. In particular, in the vicinity of the storm genesis region, the "simulated observations" from the NCEP analysis must differ significantly from those in the ECMWF analysis in order to produce the two markedly different tracks and intensities.

In this study, a total of eight 5-day OSSEs in two sets of configurations are conducted, based on the control and "observed" model runs. In the first set, all the sounding data are taken symmetrically from NCEP's analysis in the vicinity of the storm to investigate the effects of data injection with varying densities and scales on the storm track. Figure 2 depicts the distributions of dropwindsonde soundings for the first set of experiments. Experiment C1 takes one sounding at the storm center. Experiment C5 takes additional four soundings that make four corners of a squared box centered at the C1 sounding location. Each of the soundings is eight grids apart from the center on the diagonal axis of the squared box, thus making the box coverage of $16\Delta x \times 16\Delta y = 864$ km × 864 km. Experiment C9 takes additional four soundings on the sides of C5 box that are eight grids apart from the center. Experiment C13 adds four more soundings to C9 at the points halfway between the storm center and four corners of the squared box.

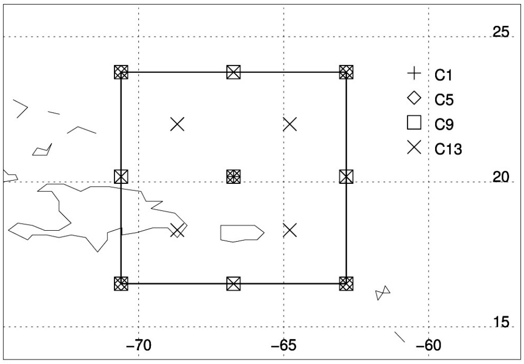

**Fig. 2.** Distribution of dropwindsonde data in the vicinity of the storm for the first set of OSSEs.

In the second set, the effects of taking "environmental observations" from NCEP's analysis are examined, as compared to the first set with "adjacent observations." Thus, a square-boxed coverage of 1728 km × 1728 km, also centered at the storm, is divided into four squared sub-boxes (864 km × 864 km) distributed in the four quadrants (i.e., NW, NE, SW, SE), each possessing 13 soundings (see Fig. 3). Results from this set of OSSEs and C13 will help reveal which quadrant of soundings plays a more important role in determining the track of Bonnie, as compared to the same number of soundings taken over the same area in the vicinity of the storm.

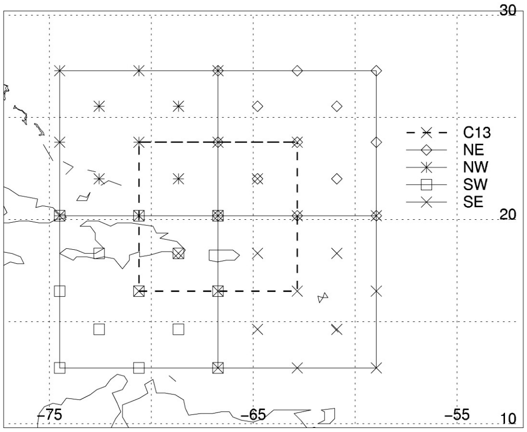

**Fig. 3.** Distribution of dropwindsonde data in the quadrant areas around the storm center with each containing 13 soundings for the second set of OSSEs. The C13 sounding locations are also plotted for comparison.

## 4. Results

Before performing various OSSEs, we noted some major differences in the initial pressure and wind fields between the NCEP and ECMWF analyses. For instance, the storm is centered at 67.70°W, 20.18°N in the NCEP analysis, but in the ECMWF analysis the storm center is about 50 km to the east of "the observed" (i.e., the NCEP analysis) (not shown). Although the associated circulation patterns are similar, the NCEP analysis exhibits the presence of more intense horizontal winds in the lower troposphere that corresponds to a 3-hPa deeper central pressure, but of weaker horizontal winds aloft near the storm center than those in the ECMWF analysis.

The ECMWF model has no bogus vortex, and thus the model TC may have the wrong position and structure. By contrast, the NCEP/GFS model at that time had a bogus vortex inserted near the correct position (personal communication, R. Elsberry, 2008). This might have caused the major difference in the initial conditions obtained from two different global analyses.

The difference fields of initial conditions between the control and the simulated observation (i.e., ECMWF minus NCEP) reveal that the ECMWF analysis show relatively strong westerly (easterly) flows at the lower levels at the north (south) semicircle, but relatively strong easterly (northwesterly) aloft at the north (south) semicircle (not shown). This implies that it has a stronger anticyclonic (cyclonic) circulation at the lower (upper) levels, which generates a weaker cyclonic vortex than the NCEP data does. In other words, to make the track forecast close to the observed (NCEP), the wind fields need a cyclonic (anticyclonic) correction at the lower (upper) levels.

We now investigate the impact of dropwindsonde data for various sounding densities and configurations. Figure 4 depicts the forecast tracks from four OSSEs, as compared to the "observed" and control run. Adding just one dropwindsonde observation (C1) near the storm center makes little change to the forecast track. With more observations (e.g., C5 and C9), track forecasts are improved, more

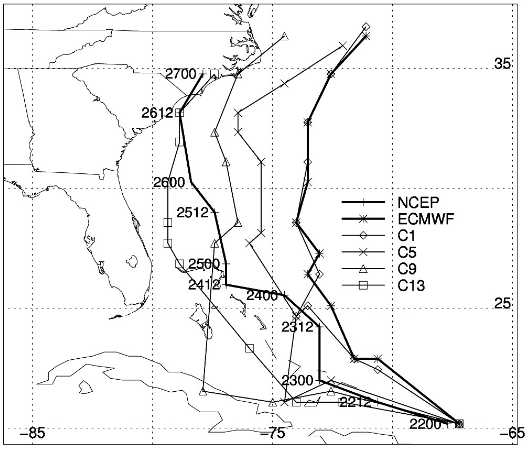

**Fig. 4.** As in Fig. 1, but for the simulated tracks from the first set of OSSEs with sounding locations given in Fig. 2. The "observed" track (NCEP) and control forecast (ECMWF) are also plotted for comparison.

significantly during the first 24 h, but they are still far from the observed (NCEP) near landfall. Incorporating 13 dropwindsonde data (C13) results in a large amount of correction to the forecast track, especially near landfall. Based on this set of OSSEs, we may state that more dropwindsonde observations in the vicinity of the storm center yield better track forecasts of TCs.

To help gain insight into the model initial uncertainties in determining track forecasts, Fig. 5 shows the difference fields of horizontal wind between Exp. C13 and the control run. Apparently, adding the 13 dropwindsonde data induces strong cyclonic corrections in the lower-level wind fields and moderate anticyclonic corrections in the upper-level wind fields. This is consistent with the difference fields at the initial time between the two analyses, as mentioned above, although the lower-level cyclonic correction is much stronger in Exp. C13. This low-level cyclonic correction appears to be responsible for obtaining the more realistic track forecasts in the early model integration period. The C13 track appears to deviate too much to the west of the "observed" because the cyclonic correction is too excessive (Fig. 5, upper panel).

Franklin and DeMaria (1992) showed adding soundings in different semicircles resulted in differ-

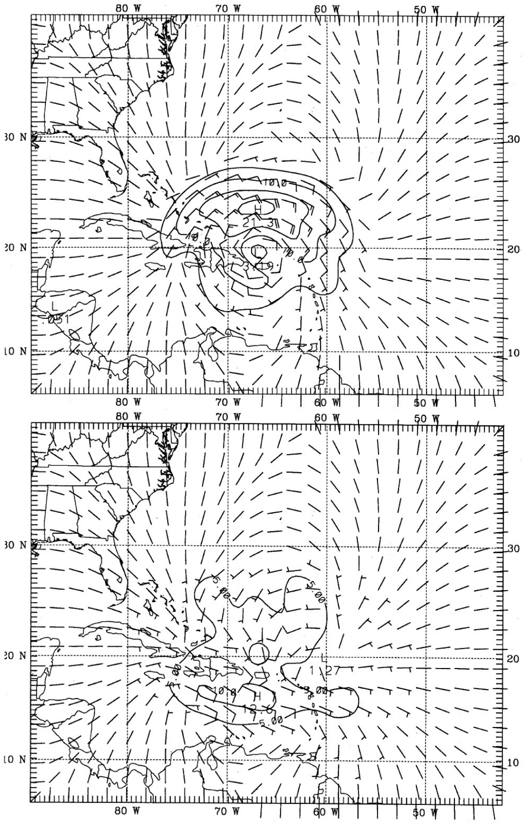

**Fig. 5.** The difference wind fields at the model initial time between C13 and ECMWF (i.e., C13 minus ECMWF) at 850 hPa (upper panel) and 200 hPa (lower panel). A full barb is 5 m s$^{-1}$.

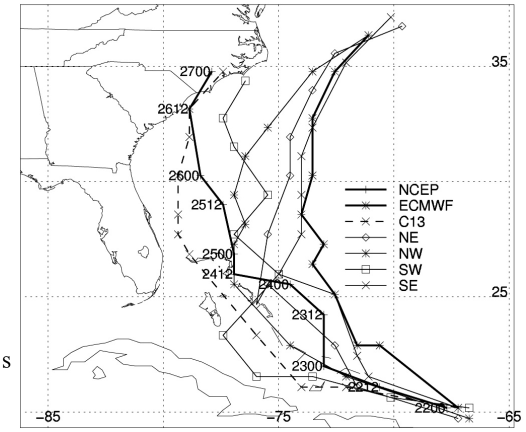

**Fig. 6.** As in Fig. 1, but for the simulated tracks from the second set of OSSEs with sounding locations given in Fig. 3. The "observed" track (NCEP), control forecast (ECMWF) and forecast based on C13 (dashed) are also plotted for comparison.

ent improvements in barotropic model forecasts. In Fig. 6, the track forecasts are compared from 4 OSSEs using the dropwindsonde soundings added in different quadrants (see Fig. 3). One should note that introducing observations in single quadrants as in Fig. 3 may lead to highly asymmetric representations of the TC vortex, which then lead to oscillations in the track as the model integration adjusts to create a more symmetric vortex (personal communication, R. Elsberry, 2008). It shows that, at the end of the 72-h integration, adding dropwindsonde data in the southwestern quadrant (i.e., SW) produces the best track forecast. Nevertheless, our results also indicate that enhanced observations in each quadrant could yield an improved forecast track. However, dropwindsonde data distributed with uniform distance around the storm center, e.g., in C13, would generate more positive impact than those in any single quadrant on the track forecasts.

## 5. Conclusions

In this study, the potential impact of dropwindsonde observations on track forecast of Hurricane Bonnie (1998) is investigated through OSSEs using the MM5 model. In general, increasing dropwindsonde observations around the storm center helps improve track forecasts. In addition, uniformly enhanced observations in the storm environment tend to produce more significant improvements in track forecasts than those enhanced observations in any of the semicircles around the storm. These results could be understood as corrections to the environmental winds for the propagation of the storm. More attention should be paid to the adjacent regions of stronger winds. A forthcoming study will be performed to examine the structures and evolution of the storm in each experiment in order to provide a more complete understanding of the mechanisms of data impact.

In conclusion, our results imply that proper designs of observational network (i.e., distribution and density) are important in the model forecasts of tropical cyclone tracks. The results also have important implications to the adaptive observations as to how effectively one should deploy dropwindsondes (e.g., Zhang and Krishnamurti, 2000). This kind of study may provide basic information on the usefulness of an observing system in field campaigns (e.g., Park, 2004). More experiments are performed for other tropical cyclones in the North Pacific basin, and similar improvements in track forecasts are observed with adequate collection of dropwindsonde data (e.g., Park *et al.*, 2004).

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