An initialization scheme for tropical cyclone numerical prediction by enhancing humidity in deep convection region

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Abstract

A nudging scheme for humidity field is implemented in the Advanced Hurricane Weather Research and Forecasting (WRF) model for tropical cyclone (TC) initialization. The scheme improves TC simulation by enhancing the TC humidity profile in deep convection regions, where uses satellite Fengyun 2 cloud-top brightness temperatures as a judging criterion. The impacts of the nudging on predicting TC intensity and structure are evaluated through the simulation of TC Khanun (2005) during its movement toward landfall at the coast of Zhejiang Province, China. During the nudging, the humidity distributions at the TC’s inner core and along its outer spiral rainbands, where deep convections occur, are both enhanced. As a result, the intensity of the vortex is enhanced, being more consistent to the best track data from the China Meteorological Administration. Specifically, the nudging modifies the simulated distribution of humidity according to convective activities captured by the satellite, and therefore adjusts the development of deep convection in the model, which then influences the intensity and size of TC vortex through diabatic heating.

During WRF simulation, the TC vortex initialized from the humidity nudging is dynamically and thermodynamically balanced with the background field, favoring a steady development of vortex’s intensity and structure. Due to better simulation of TC inner core and outer spiral rainbands, WRF simulation skills of TC intensity and track are improved.
1. Introduction

Recently, numerical forecast models for tropical cyclone (TC) at high resolution have been improved greatly thanks to advances in physical parameterization and computer architecture. However, due to insufficient observations over the ocean, initial vortices provided by the large-scale analysis from the operational centers are often too weak and sometimes misplaced, making it necessary to introduce a bogus vortex into model’s initial condition (Zou and Xiao, 2000). There are mainly three kinds of TC initialization methods associated with direct or indirect use of bogus vortex. The first kind substitutes an initial vortex specified by some balanced equations (such as the Rankine vortex implanted by Lord, 1991) or by an assimilation technique (e.g., Four-dimensional variational assimilation by Zou and Xiao, 2000) based on certain observed parameters. The second one uses the same forecast model to “spin up” an initial vortex before making a prediction (Kurihara and Ross, 1993; Kurihara et al., 1995). And the third one improves the model initial conditions via a physical initialization procedure using satellite-based observations (Krishnamurti et al., 1993; 1995; 1997; 1998; Ma et al., 2007).

As an example of the first kind of TC initialization scheme listed above, Lord (1991) first implanted a synthetic (bogus) vortex into his global forecast model. The bogus vortex was specified based on the observed TC information, such as the radius of the maximum wind, the position of the maximum vorticity, and the intensity of the surface low pressure system. Zou and Xiao (2000) proposed a variational bogus data assimilation (BDA) scheme with a 4D-VAR framework to generate the TC vortex using a specified surface low based on a few observed parameters. It is found that, through their BDA procedure, the adjustments could be done on all the model fields at the initial time, while the assimilation was only conducted on some of the observed
Another advantage of the BDA scheme is that it is convenient to incorporate satellite and radar data into the hurricane initialization procedure. Many successful simulations, including prediction of TC movement and structure, have been conducted by assimilating satellite and radar data based on BDA scheme (Zhao, 2005; Zhang et al., 2007; Liang et al., 2007; Montrotty et al., 2008). 4D-Var uses the actual forecast model to provide a strong dynamical constraint. The generated initial vortex not only fits the bogus specification, but also is consistent with the model resolution and physics. However, the real-time operational application of TC BDA with a 4D-VAR framework is too expensive due to its iterative minimization procedure; therefore, Xiao et al. (2006, 2009) extended the work of Zou and Xiao (2000) to implement the BDA scheme in a 3D-VAR framework. 3D-Var systems control the analysis adjustment by its dynamical and statistical balance constraints, and allow the TC structure to be developed in a balanced manner.

For the second kind of TC initialization, a vortex constructed by time integration of hurricane prediction model was proposed which is model compatible (Kurihara and Ross, 1993; Kurihara et al., 1995; Liu et al., 1997; Nguyen and Chen, 2011). At the Geophysical Fluid Dynamics Laboratory (GFDL), the axisymmetric component of the initial vortex was bred through the axisymmetric hurricane prediction model and the asymmetric component was produced by the time integration of a simplified barotropic vorticity equation. Finally the initial analyzed vortex was removed and the bogus vortex was inserted into the large scale analysis. Liu et al. (1997) used the fifth-generation Pennsylvania State University–National Center for Atmospheric Research (PSU–NCAR) non-hydrostatic Mesoscale Model (MM5) to integrate a vortex in the coarsest domain (54 km grid), and implanted the vortex into the model initial conditions for all domains. Recently, a model self-bogusing vortex was
constructed by cycle runs using the Weather Research and Forecasting (WRF) model to provide high-resolution initial conditions for TC simulation by Nguyen and Chen (2011). This model self-bogusing vortex initialization scheme showed significant improvement in terms of thermodynamic structures of the vortex and TC intensity forecast.

For the third kind of TC initialization, because of the importance of diabatic heating for TC forecast, physical initialization schemes have been developed in recent years. Davidson and Puri (1992) utilized satellite cloud imagery to incorporate tropical convective heating sources into model initial conditions, and tested the performance of this tropical diabatic initialization scheme in many real-case simulations. Encouraging results were found for short-term predictions of both TC and heavy rainfall events. It is demonstrated that physical initialization is a useful procedure for improving simulation of initial TC rainfall rate by making use of satellite and rain-gauge based measurements of rainfall (Krishnamurti et al., 1993; 1995; 1997; 1998; Ma et al., 2007; Pattnaik et al., 2011).

In a recent study, Wang (2009) demonstrated the importance of latent heat release in the outer spiral rainbands on the size and intensity simulation of TC. The humidity distribution in the TC inner core and outer spiral rainbands could adjust the downdraft intensity and SLP (sea level pressure) gradient around TC by latent heating and cooling, and finally dominate the TC inner-core’s size and intensity (Wang, 2009). The intensity change of TC is shown to be very sensitive to near-core moisture perturbations (Chu et al., 2011). A physical initialization scheme associated with moisture adjustment and latent heating determined from satellite cloud-top brightness temperature was used by Orlandi et al. (2010) to improve the representation of African meso-scale convective systems (MCSs) in the model. In this scheme,
appropriate modifications on the model-humidity profile were performed to trigger convections at the right places, which led to the improvement of geographical distribution and temporal evolution of simulated African MCSs. Humidity profile is crucial for the representation of diabatic processes associated with TC.

In the present paper, a physical initialization scheme is proposed to improve TC simulation by enhancing the TC humidity profile in deep convection region, through humidity nudging and the use of Fengyun 2 (FY2) cloud-top brightness temperature data. Section 2 of this paper describes methodology. Section 3 examines the evolution of bogus vortex during the TC initialization procedure. Section 4 focuses on the sensitivity of TC intensity and track simulations to the humidity forcing. The subsequent prediction of TC development is investigated in section 5. Conclusions of this paper are given in section 6.

2. Methodology

a. The humidity nudging scheme based on cloud-top brightness temperature of FY2

A recent study by Wang (2009) demonstrated the importance of humidity and latent heat release in the outer spiral rainbands in simulating the size and intensity of TC. In association with the humidity, the wind-induced surface heat exchange (WISHE; Emanuel, 1986; Rotunno and Emanuel, 1987) mechanism plays a critical role in the rapid intensification of TC. Particularly, as the vortical hot towers (VHTs) associated with TC deep convection play an important role in TC rapid intensification (Hendricks et al., 2004), it is critical to represent the deep convection and its moisture structure correctly for successful TC intensity prediction.

In the present study, to improve the moisture structure and deep convection of
TC in the model, the nudging scheme based on the approach proposed by Davolio and Buzzi (2004) is used. This scheme was first used in the assimilation of precipitation observations in the extra-tropics, based on which Orlandi et al. (2010) implemented a modified nudging procedure in a meso-scale numerical model to improve the representation of MCSs in West African warm-season rainfall. Firstly, the middle- and low-level air is hypothesized to be nearly saturated in the convective zone. Then, the convective precipitation is isolated from stratiform precipitation by the satellite observations of cloud-top brightness temperature (CTBT), and model humidity profile is corrected in the convective zone, which could avoid the uncertainty produced by precipitation estimation (Ebert et al., 2007).

The nudging scheme developed by Orlandi et al. (2010) is implemented here for the simulation of TC. It is hypothesized that the middle- and low-level air masses within the TC deep-convection regions are nearly saturated during the nudging procedure. The nudging scheme compares brightness temperature evaluated by the Community Radiative Transfer Model (CRTM) and that observed from FY2 satellite in high temporal (1 h) and high spatial (0.1° × 0.1°) resolutions so that it can detect the activity of convection in the WRF model. CRTM was developed by the U.S. Joint Center for satellite Data Assimilation for rapid calculations of microwave and infrared radiances observed by various instruments onboard spacecraft for a given state of the atmosphere and the earth’s surface. It includes components that compute the gaseous absorption of radiation, absorption and scattering of radiation by hydrometeors and aerosols, and emission and reflection of radiation by ocean, land, snow, and ice surfaces. All of these component results are then used to perform accurate radiative transfer to yield simulated CTBT with output data and surface parameter of the WRF model in the present study. The nudging amplitude of the mixing ratio profile within
the TC deep-convection regions is then tuned. The mixing ratio profile for non-deep-convection areas can be modified through the horizontal advection of the model. Through the humidity nudging, the simulated humidity profile can be modified. Most importantly, the numerical simulation of TC deep convection is expected to be improved, and so is the prediction skill of TC intensity. The deep-convection areas are determined by a criterion of the CTBT smaller than -43 °C, which is the same as that used by Davolio and Buzzi (2004) and Hendon and Wood-berry (1993). Within these deep-convection areas, the mixing ratio \( q_m(k) \) at each model level \( k \) and each grid point is modified. The nudging scheme compares the CTBT evaluated by CRTM with that observed by satellite, and then according to the development of convection, the model mixing ratio profile is modified appropriately through the following procedure.

\[
q(k) = q_m(k) + \varepsilon \cdot \Delta q(k), \tag{1}
\]

\[
\Delta q(k) = -\frac{\nu(k)}{\tau} [q_m(k) - q_s(k)] \times \Delta t, \tag{2}
\]

where \( q_s \) is the saturation mixing ratio, which is evaluated with respect to liquid water above 0 °C, while below 0 °C, a mixed-phase cloud is considered. \( \nu(k) \) is a weighting function used in determining the vertical profile modified by the nudging procedure. It is set to 1 bellow 400 hPa and to 0 from 400 hPa up to the top of the model. Parameter \( \tau \) and \( \Delta t \) are the nudging relaxation time and the nudging period, respectively. Considering the temporal resolution of CTBT observation data and the computational stability, also based on many test experiments, the values selected in the present paper is 1 h for \( \tau \) and 30 min for \( \Delta t \). The intensity of the moisture profile modification depends on the common actions of parameters \( \varepsilon \), \( \tau \) and \( \Delta t \). In the control simulation (Exp CTL), if the CTBT from the CRTM is higher than the
satellite observation, which means the convection in the model is less intense than observation, $\varepsilon$ is set to 1 for modifying the model humidity profile toward a saturation state. In the opposite situation, the model has produced unrealistic convection already, so $\varepsilon$ is set to 0.25 to enhance the humidity profile with a weaker intensity. The value of parameter $\varepsilon$, which is independent on TC case studied, is set to increase the bogus vortex’s intensity growth speed properly on condition that the computational stability is guaranteed. The comparison between the CTBT from the CRTM and that from the satellite observation is performed every 30 min while the satellite data is updated once per hour.

The nudging is carried out iteratively until the SLP difference between the bogus vortex and that of the observation at T=0 h becomes less than 5 hPa. After that, the model is integrated normally to T = 0 h, so that the bogus vortex could get corresponding with the TC initial environment fields. The whole vortex breeding procedure spends 24 hours. It should be noted that this scheme does not assimilate satellite observation, but it uses satellite brightness temperature to identify where to do the nudging.

b. The inserting procedure for TC bogus vortex

There are many sophisticated techniques for TC initialization with bogus vortex, such as the vortex-relocation scheme applied by Kurihara et al. (1995), the 3D-VAR method utilized by Xiao et al. (2006), and the inserting method by Liu et al. (1997). Considering the complexity and practical effects of these techniques, the method similar to Liu et al. (1997) is implemented in this study.

The detailed inserting procedure is as follows. After the vortex breeding procedure, the TC bogus vortex bred by the WRF model approaches the observed TC vortex. Firstly, the three-dimensional (3D) data (horizontal wind, geopotential height,
temperature and SLP) of the bogus vortex in D1 is picked up within the range of TC vortex circulation defined by the maximum radius of gale-force wind. Then, the bogus vortex is embedded into the background fields and relocated according to the observed position of TC at T= 0 h. There is a linear transitional region from inserting bogus vortex to keeping the background circulation between 0 and 100 km away from the gale-force wind radius, within which the intensity of embedded vortex circulation decreases linearly as merging with the background fields. The fields of inner domain (D2) are interpolated from the results of D1 which has been inserted by the bogus vortex.

c. Case description

The physical nudging scheme is utilized and evaluated for the simulation of TC Khanun (2005) in this paper. TC Khanun intensified into a typhoon at 1800 UTC 8 September 2005. It moved northwestward and made landfall at the coast of Zhejiang Province, China at 0700 UTC 11 September, with a central SLP of 945 hPa, a maximum surface wind speed of 50 m s\(^{-1}\), and the radius of damaging-force wind (25.7 m s\(^{-1}\)) of 150 km. The TC intensity given by the GFS operational model analysis of NCEP is distinctly underestimated. For instance, at 0000 UTC 8 September, the observed central pressure of Khanun is 985 hPa, while that in the GFS analysis is only 1004 hPa. During the course of TC rapid intensification (from 0000 UTC 8 September to 0000 UTC 9 September), the observed central pressure of Khanun dropped by about 20 hPa, whereas the change in the GFS analysis was only 2 hPa. Therefore, the GFS analysis of the TC only has a central SLP of 997 hPa and a maximum wind speed of 22 m s\(^{-1}\) before Khanun's landfall, which is much weaker compared with the observed 945 hPa for the central pressure and 50 m s\(^{-1}\) for the maximum wind speed.

The above discussions indicate that it is necessary to incorporate a TC initialization
scheme into the numerical model for a better simulation of TC, especially for the intensity prediction.

d. Model description and experiment design

In this study, the Advanced Research WRF (ARW) is used, which employs fully compressible non-hydrostatic dynamical framework, the terrain-following Euler mass coordinate, and the horizontal Arakawa-C grid. To improve the prediction skill of the sudden intensification before TC landfall, to overcome the underestimation of sea surface momentum exchange under strong wind and the ill simulation of TC rapid intensification, Davis et al. (2008) revised the model's surface flux exchange coefficients (such as that of momentum, heat, and water vapor) substantially, and coupled it with a one-dimensional ocean mixing layer model. These above configurations construct the Advanced Hurricane WRF (AHW) model. The roughness in the AHW model has been modified according to the results of flume experiments of Donelan et al. (2004) in order to correspond to the drag coefficient and 10-m wind speed under the condition of strong wind. Then, the characteristic velocity, temperature, humidity, and various surface fluxes are calculated based on the similarity theory (Davis et al. 2008). In this study, the new scheme of surface flux exchange in the AHW is used with the roughness of thermodynamic variables and humidity kept constant. The model is two-way interactively nested, with 12- and 3-km horizontal grid resolutions, respectively. The outer 12-km coarse resolution domain (D1) contains 424×401 horizontal grid points, while the inner 3-km fine resolution domain (D2) has 553×605 grid points (Fig. 1). During the humidity nudging procedure, the inner domain is fixed at the position showed by Figure 1, while it moves in accordance with the TC vortex center during the subsequent forecasting
period. During the discussion in this paper, except for rainfall comparisons which are conducted on D1, all the other analyses are done on D2. After the humidity nudging procedure, the bogus vortex will be inserted into the model initial condition of D1, and the initial condition of D2 is interpolated from the results of D1. There are 35 $\sigma$ layers in the vertical direction for both domains, with the model top defined at 50 hPa. The Thompson microphysics scheme (Thompson et al., 2008), which could distinguish cloud water, rain water, ice, graupel, and snow, and the YSU (Yonsei University) planetary boundary layer parameterization (Hong et al., 2006) are used for both domains. The modified version of Kain-Fritsch cumulus convective parameterization scheme (Kain and Fritsch, 1990; 1993; Kain, 2004) is used in the coarse domain, and no convective parameterization is used for the inner domain since explicit microphysics is at play. The initial and boundary conditions of the simulation are from the 0.5°×0.5° Global Forecast System (GFS) model operational analysis data of the National Centers for Environmental Prediction (NCEP), with a time interval of 6 h.

Figure 2 is the schematic illustration of the overall strategy of the vortex-generating scheme for TC initialization by enhancing the environmental humidity. During the nudging procedure, the moisture profile of the model is modified gradually after comparing brightness temperatures observed from satellite and derived by CRTM model at a nudging window of 30 min and relaxation time of 1 h, while the satellite data is updated once per hour. The background fields of target analysis for the nudging is first obtained from the 0.5°×0.5° GFS analysis data at 0000 UTC 9 September 2005, and this time, set as T=0 h, is the base time of the TC forecasting and the target time of the initialization procedure. Then, the initial bogus TC, bred by the nudging procedure that has been introduced in section 2a, is inserted into the
background fields and relocated according to the observed position of TC at T= 0 h.
And the detailed inserting procedure has been described in section 2b. The subsequent
prediction of TC covers a period of three days (72 h) from 0000 UTC 9 September to
0000 UTC 12 September, during which period the observed TC comes through rapid
intensification and makes landfall at Taizhou, Zhejiang Province at 0650 UTC 11
September.
To assess the impacts of the nudging scheme, a set of contrastive experiments
with different humidity forcing intensity or different TC bogus technique is conducted.
These sensitivity experiments will be analyzed in detail later in the paper.

3. Evolution of TC vortex during the nudging cycle
To assess the performance of the initialization scheme, the iteratively updated
bogus TC vortex during the vortex breeding procedure (i.e., from T= -24 h to T= 0 h)
is examined through comparison of the CTBT from the model simulation and
observation. During the nudging process, the TC circulation and physical structure are
modified gradually.

Figure 3 shows the comparison between CTBT from the stationary satellite FY2
at the 11 μm channel and that from the WRF simulation via the CRTM. It is shown
that when using the observed CTBT smaller than 230 K as the criterion of deep
convection (Davolio and Buzzi, 2004) in the nudging procedure, the area of deep
convection simulated by the model is slightly larger than the satellite observation. In
the central region of the TC, the simulated CTBT is clearly higher than the
observation, indicating less deep convection in the simulation. On the other hand, in
the outer regions of the TC, the simulated CTBT is lower than the observation, with
evident divergent anvil clouds and a larger coverage of high clouds. At the early stage
of the simulation, there are scattered convective cells around the TC circulation; thus,
the features of simulated CTBT are dominated by many isolated low-value zones. With the humidity nudging, the simulated CTBT of the convective cloud clusters near the TC eye is reduced gradually, indicating the convective actions near the eye become vibrant.

The intensity and structure of the simulated TC have been adjusted extensively through the humidity-nudging TC initialization procedure. At 12 h of humidity nudging (T= -12 h), the simulated Radius of Maximum wind (RMW) is about 200 km and the maximum wind speed is only 15 m s\(^{-1}\) (Figs. 4a-b). As the integration proceeds, deep convection evolves violently in accordance with the humidity forcing. As a result, the RMW reduces rapidly to about 80 km, and the tangential wind speed and the 3D coverage of gale-force wind of simulated TC are simultaneously enlarged, showing a TC structure more consistent to the satellite observation (Figs. 4c-h). It can also be seen from Fig. 4 that in the TC wind field, the speed of radial wind is far less than that of tangential wind. At the early stage of nudging, radial convergence is dominant near the TC vortex, with the most intense convergence at the TC center, while weak divergence appears in the upper troposphere. As the convection evolves, the low-level radial convergence enhances gradually, with the maximum convergent center concentrating at about 50-80 km from the TC center, and both the thickness and intensity of the low-level inflow are enhanced. The features of TC eye and eyewall become more and more clearly during the nudging process. After 18 h of nudging (T= -6 h), the maximum azimuthally-averaged tangential wind speed has reached to near 30 m s\(^{-1}\) (Fig. 4f). Moreover, in the center of the TC the outflow radial wind speed intensifies extensively. The maximum outflow within the TC eye is 4 m s\(^{-1}\) and the maximum low-level inflow 6 m s\(^{-1}\), with intensified convergence near the TC eyewall (Fig. 4e). The significant diabatic heating (greater than 1×10\(^{-3}\) K s\(^{-1}\)), which is initially
located at the TC center, migrates outward to the eyewall vicinity along with the movement of convergence center as the nudging proceeds. Meanwhile, in the vertical direction the maximum diabatic heating core transfers from the middle troposphere to the upper troposphere gradually, in accordance with the strengthening of TC vortex. For instance, at the initial stage of TC vortex bogusing, the diabatic heating core is located at about 800 to 400 hPa (Fig. 4a), and moves upward to about 700 to 300 hPa when the intensity of the bogus vortex approaches to that of the observation (Figs. 4e and 4g). Hack and Schubert (1986) found that the rapid intensification of TC was closely related to the vertical structure of heating source and the magnitude of inertial stability. The rapid intensification efficiency of TC was higher under the condition of lower heating source level and smaller inertial stability. During the humidity nudging procedure, the simulated heating source is located at a very low level, the inertial stability is very small from 12 h to 18 h of nudging (T= -12 h to T= -6 h), and the simulated TC during this period is still very weak. Therefore, as indicated in Hack and Schubert (1986), the intensity of TC increases very rapidly from 12 h to 18 h. After 18 h of nudging, the growth of tangential wind speed slows down, which only increases by 5 m s\(^{-1}\) up to the target analysis time (T= 0 h). During the course of TC intensification, the warm-core structure has changed obviously. At first, weak warm core only exists around the TC eye, and the temperature perturbation at the TC center rises from 2 °C to 6 °C from 12 h to 15 h of nudging because of the TC intensification (Figs. 4b and 4d). Influenced by the distribution of simulated diabatic heating, the vertical position of the warm core of the bogus vortex in the humidity nudging experiment is a little lower. When the bogus TC becomes mature, its warm core is located at about 600 hPa (Figs. 4f and 4h). Figure 5 shows the increment of Exp CTL compared with Exp 00, including geopotential height, temperature and horizontal
wind at 850 hPa and 500 hPa after the vortex breeding procedure. It is showed that the
crements of 850-hPa dynamical and thermodynamic fields are larger than that of
500-hPa fields. The geopotential height increment of TC center is as large as 320 gpm
and the maximum increments of temperature and maximum wind speed reach to 8 °C
and 20 m s⁻¹, respectively. The increment of low-level temperature exists both around
the TC vortex and within outer spiral rainbands while that of upper-level temperature
mainly located near TC center. Both the increments of TC wind speed and geopotential
height are mainly located around TC center.

The above discussions indicate that during the humidity nudging, the bogus TC
intensifies rapidly with its structure more reasonable, favoring subsequent prediction
of TC evolution.

4. Sensitivity experiments on humidity nudging

To investigate the response of TC initialization to the modification of the forcing
term through modulating the humidity profile within the deep-convection regions,
sensitivity experiments are designed (Table 1) and analyzed by changing the value of
parameter ε in Eq. (1). In Exp CTL, if the simulated convection within the
deep-convection regions is more intense than the satellite observation, ε is set to
0.25; otherwise, ε is set to 1. In the sensitivity experiments, the parameter ε in the
deep-convection regions is increased to 0.5 and reduced to 0 when simulated
convection is more intense than the satellite observation in Exp 1 and Exp 2,
respectively. Furthermore, Exp 00 (see Table 1) is performed with no humidity
enhancing (ε =0 in the whole deep-convection region), as a reference of the nudging
effect.

The structural evolution of the bogus vortex simulated by Exp CTL is studied
and compared with other sensitivity experiments in Fig. 6, which shows the 700-hPa radar reflectivity and 10-m wind speed from 3 h to 21 h of the humidity nudging. At the initial stage, the active convections in Exp CTL are mainly located near the TC center. After that, many convective cloud clusters develop simultaneously, forming the TC eyewall. Meanwhile, the outer spiral rainbands are gradually organized by the TC vortex. The above features can be seen in the CTBT (Fig. 3), although the spiral bands’ characteristics are more distinct in the simulated radar reflectivity. At 15 h (T= -9 h) of the nudging (Fig. 6), there are two spiral rainbands located at the northwest and southeast quadrants of the TC vortex, respectively, which slowly rotate anticlockwisely as the TC system evolves. The features of spiral rainbands shown in Fig. 6 are much more similar to the rainbands’ structures indicated in the observed CTBT, but different from that of the CRTM (Fig. 3). The radius of damaging-force wind in Exp CTL does not increase extensively, but maintains at about 120 km after the intensification of TC. Furthermore, during the process of TC axisymmetrization after 18 h of the nudging, the distribution of the radius of damaging-force wind also becomes symmetric around the TC center. The radius of TC eyewall and the RMW are about the same (50-60 km) in Exp CTL, consistent with the small scale of observed TC Khanun.

In Exp 00, the simulated deep convection starts up very late while the disorganized TC vortex remains very weak during the whole simulation. As a result, there were no TC eyewall and spiral rainbands in Exp 00 (Fig. 6), the SLP decreases by only 3 hPa and the maximum wind speed increases by only 6 m s⁻¹ within 24 h of the nudging. The above results imply that the humidity nudging favors the rapid intensification of simulated TC. It is supposed that the bogus vortex’s intensity and structure can also be affected by the extension and intensity of humidity forcing. To
test this hypothesis, Exp 1 and Exp 2 are carried out with the humidity forcing intensity doubled and shut off, respectively, when the simulated CTBTs within the deep-convection areas are lower than the satellite observation. It is shown in Fig. 3 that the regions where simulated convections are more active than the observation mainly correspond to TC periphery and spiral rainbands. As the humidity forcing’s amplitude at these places are doubled, the simulated convective development in the spiral rainbands also becomes stronger in Exp 1 (Fig. 6). Furthermore, due to the increased transportation of moisture and energy through the spiral rainbands to TC inner core, the evolutions of the minimum SLP and maximum wind speed in EXP 1 are accelerated (Fig. 7). Compared with Exp CTL, the simulated TC vortex in Exp 1 is slightly stronger and larger. However, the SLP and 700-hPa radar reflectivity structure of TC vortex in Exp 1 is very close to those of Exp CTL. Therefore, the main cause of different TC intensity and size between the two experiments is the rapid TC growth in Exp 1. In comparison, Exp 2, which does not change humidity at all when the simulated CTBT is lower than the satellite observation within the deep-convection regions, possesses weaker enhancement of humidity at TC periphery and spiral rainbands than Exp CTL and Exp 1. As a result, the simulated TC in Exp 2 shows less organized spiral rainbands, weaker intensity, and less symmetric characteristics, demonstrating the importance of humidity nudging in TC intensity and structure simulation.

The simulated TC intensity evolutions in Exp CTL, Exp 1, and Exp 2 (Fig. 7) indicate that the SLP drops and the 10-m wind speed increases rapidly with model integration. After about 12 h of the nudging, the deep convective systems around TC vortex center and within spiral rainbands have developed; therefore, the simulated TC in all three experiments intensifies rapidly, with much faster growth for stronger
humidity forcing. When the bogus vortex approaches the observed intensity of TC (i.e., at 21 h of the simulation), the humidity nudging is turned off. After that, the convective actions around TC vortex gradually weaken (Fig. 7). From 3 h prior to the initial time, the simulated maximum wind speed sustains while the simulated SLP drops a little (Fig. 7). The changes of humidity forcing intensity through altering parameter $\varepsilon$ mainly influence the growth speed of TC intensity. And the ultimate evolution intensity of bogus vortex is determined by the shutting time of humidity nudging and the observed TC intensity. During this procedure, if the initial vortex is weaker or the observed TC vortex is stronger, the increasing of TC bogus intensity is more rapidly. The TC rapidly intensification could then influence the forecast of TC.

5. Impact of nudging on prediction of TC development using WRF

After the vortex breeding procedure, the bogus vortex has developed extensively, and both its intensity and structure are closer to the observed TC vortex. The vortex circulation generated from the nudging procedure is then extracted (from the nudging result) and inserted into the initial field of the WRF model at the base time of simulation ($T=0$ h; Fig. 2).

Comparing the subsequent TC predictions of the three humidity nudging experiments (Exps 1, 2, and 00) and that of the experiment with the simple TC bogus scheme in the WRF model (WRFBogus) which implements simple Rankin vortex, it is found that all three humidity nudging simulations (Table 1) can forecast the TC track reasonably (Fig. 8). The initialization scheme in WRFBogus experiment detects and removes the existing TC vortex and inserts a new Rankine vortex through stream function and potential function. And at the same time, the humidity distribution around TC vortex is revised, which is set to 95% within the TC’s RMW and decreases
linearly outside TC’s RMW.

After about 63 h, the simulated landfall locations of the three humidity nudging experiments are very close to that of the observation. The track of Exp 00, which has no bogus vortex, is very complicated with the TC center vibrating a lot. Its forecasting error is much larger than the other three humidity nudging simulations (Fig. 8). Before 39 h of simulation, the track of WRFBogus is nearly identical to that of the observation. After that, the TC track of WRFBogus turns northward suddenly, resulting in about 150-km difference on landfall location from the observation.

For TC intensity prediction, the humidity nudging and WRFBougs simulations generally reproduce the observed evolution of TC maximum wind speed and minimum SLP, especially in terms of rapid intensification and the sudden weakening during landfall (Fig. 9). The intensities of initial TC vortex (T=0 h) in the three humidity nudging simulations are different. For Exp 1, the initial minimum SLP is about 9 hPa lower than the observation. As a result, although the occurrence time of the lowest SLP is mainly the same as that of the observation, its pressure value is about 10 hPa lower (Fig.9). On the other hand, the initial minimum SLP in Exp 2 is 12 hPa higher than the observation (the highest of the three humidity nudging simulations). However, after 50 h of TC development, the simulated TC vortex in Exp 2 reaches the observed intensity. In Exp CTL, the initial TC intensity is within 2 hPa difference from that of the observation. But because of the cold start of the WRF model, the simulated TC does not intensify rapidly until 12 h later, resulting in weaker intensity than the observation at the early stage. Later on, as that in Exp 2, the simulated minimum SLP in Exp CTL agrees with the observation very well after 50 h of simulation. In WRFBogus, although the observed minimum SLP and maximum wind speed have been assimilated into the model during the initialization procedure,
the SLP of the generated vortex in the initial condition is still much higher than the
observation before landfall. The TC vortex in WRFBogus stops to intensify after 32 h
though forecasted intensity from WRFBogus is more similar to that from Exp 2 before
40-h forecast, causing intensity much lower than the observation and Exp 2 thereafter.
In Exp 00, the initial TC is too weak to develop, thus the TC vortex simply maintains
its initial intensity throughout the 72 h of simulation. It should be noted that, because
the initial condition of D2 (T=0 h) is interpolated from the results of D1 which has
been inserted by the bogus vortex for taking into account the computational stability,
the SLP and the maximum 10-m wind speed on D2 at the end of Fig. 7 (T=0 h) are
different from those at the beginning of Fig. 9 (T=0 h).

The evolution feature of TC maximum wind speed is very similar to that of
minimum SLP. All four bogus experiments (including three humidity nudging ones
and WRFBogus) can predict the strengthening process of TC maximum wind speed
very well. There exists an adjustment period from 9 to 15 h of simulation in Exp
WRFBogus. Although the TC vortex intensifies, the simulated maximum wind speed
is still less than the observation. In comparison, in the three humidity nudging
experiments, the maximum wind speed intensifies very rapidly after just 6 h of
adjustment, which is shorter than that of WRFBogus. Moreover, the intensification of
wind speed in the humidity nudging experiments begins earlier than the depression of
SLP. In Exp 1, the initial TC intensity is a little stronger than the observation; and
during the WRF simulation, it maintains the highest maximum wind speed among the
five experiments.

On the whole, the generated TC vortex through the humidity nudging scheme
adapts very well to the WRF model and its dynamics/thermodynamics constraints. As
a result, the TC track prediction is comparatively steady and not very sensitive to the
magnitude of humidity nudging intensity. The intensities of TC (e.g. the maximum
strength, the peak time, and the intensification speed) among all nudging experiments
have some differences, thus the parameters in Equations 1 and 2 must be tuned
carefully to generate the best forecast.

Comparing with the results of WRFBogus, the errors in TC track simulation in
the three humidity nudging experiments (excluding Exp 00) are all much smaller.

Figure 10 shows the comparison of the circulation structure of TC vortex
between Exp CTL and WRFBougs after 6 h of integration (T= 6 h). At that time, there
is only 6-hPa difference in minimum SLP between the two experiments and their
850-hPa maximum wind speed is very close to each other (both around 40 m s\(^{-1}\)). In
WRFBogus, the maximum 850-hPa wind speed is located at the northwest quadrant of
TC vortex, which is to the right side of the TC moving direction. However, the highest
850-hPa wind speed in Exp CTL is suited on the east side of moving TC vortex. Its
asymmetry feature is induced by the effects of spiral rainbands in the southeast of the
TC vortex and the movment of TC. In Exp CTL, this kind of asymmetric feature of
wind field has been represented in the initial bogus vortex through the humidity
nudging. For the 850-hPa TC circulation structure, the changing of wind vector in the
simulated TC vortex generated from the simple Rankin vortex in WRFBogus is
relatively uniform between 0- and 180-km radius from the TC center. Meanwhile,
different from that of WRFBogus, the wind vector changing in Exp CTL is mainly
located at 180 km radius from the TC center, and the vertical extension of cyclonic
vortex in Exp CTL is very high, with a clear cyclonic circulation at 250 hPa and an
associted wind speed of ~30 m s\(^{-1}\) (Fig. 10). Particularly, between T= 0 h and T= 15 h,
WRFBogus experiences an adjusting process, during which the 10-m maximum wind
speed decreases and the SLP increases a little (Fig. 9). The initial bogus vortex in Exp
CTL is more suitable to the WRF model, which can keep its intensity and structure information after 6-h integration and adjustment and evolve steadily during the whole 72-h simulation.

The convective systems in TC inner core start to develop after 6-h integration in all four bogus experiments. Figure 11 shows the 700-hPa radar reflectivity of these simulations. One can see that the speed of the triggering of deep convection in each simulated vortex is directly impacted by the intensity of initial bogus vortex. For instance, the initial vortex in Exp 1 is the most intense, so its radar reflectivity at T= 6 h is the highest and the area of positive-value echoes is the largest among the four simulations. All three humidity nudging experiments can reasonably predict the TC outer spiral rainbands, while Exp WRFBogus produces almost no outer spiral rainbands. The explanation is that the humidity nudging scheme, in which the initial TC vortex is generated through positive feedback of diabatic heating under the control of background circulation, mostly emphasizes the interaction between TC vortex and the environmental circulation. Moreover, with the help of vortex relocation, the TC vortex structure becomes more consistent with the background field. In WRFBogus, its bogus vortex is the simple symmetric Rankin vortex, so the background circulation has not been taken into account. Although an interaction between background circulation and bogus vortex does happen during the simulation of WRFBogus, the outer rainbands are very weak and develop slowly due to the longer time of model adjustment.

Comparing the rainfall rate simulated by CTL with that produced from the passive microwave (TMI) sensors on board the Tropical Rainfall Measuring Mission (TRMM) satellite, we can see that the humidity nudging experiments generally reproduce the structure of the outer spiral rainbands, the size of TC eyewall, and the
development of TC deep convection at T= 30 h (Fig. 12). But, during the whole 72-h simulation, the TC inner core in WRFBogus is much smaller than the TRMM observation, and its horizontal coverage of the TC surface low-pressure vortex defined by the 1000-hPa isobar is slightly larger than the observation. Therefore, the pressure gradient simulated by WRFBogus is smaller, and the range of damage-forcing wind is smaller, too, compared with those of the three humidity nudging experiments. The developed TC structures in Exp CTL, Exp 1, and Exp 2 are very similar to each other with only some differences in terms of the values of minimum SLP and maximum wind speed influenced by their different initial vortex intensity for the WRF simulation. Similarly, their rotational velocities and distributions of outer spiral rainbands only differ a little (Fig. 11).

Figure 13 indicates the vertical distribution of temperature and specific-humidity increment comparing with Exp 00 (Figs. 13a-b), horizontal wind speed, PV, and vertical circulation (Figs. 13c-d) in Exp CTL and WRFBogus along the TC moving direction (Line AB in Fig. 11) at T= 6 h. There is a distinct warm-core structure located at 200-300 hPa in Exp CTL. But the positive temperature increment in WRFBogus is abnormally large in coverage, which disagrees with the common warm-core feature of TC. The humidity increment in Exp CTL is mainly located in the regions with active convection, i.e., the TC eyewall and outer spiral rainbands, which is the same as that simulated by WRFBogus. The convections in Exp CTL, especially those in the outer spiral rainbands, are more vigorous than those in WRFBogus, as supported by the radar reflectivity and PV intensity. As a result, the value of maximum wind speed is larger and the vertical extension of gale wind is higher in Exp CTL compared with WRFBogus. For the vertical circulation of TC simulated by Exp CTL, updraft dominates the TC eyewall, while downdraft exists
within the TC inner core. The vertical shear of horizontal wind in Exp CTL is weak easterly. These features are consistent to the observations. After 30 h of integration, both WRFBogus and Exp CTL predict the TC warm-core structure and the deep convective clouds around TC eyewall very well (Fig. 14). However, comparison with the distribution of radar reflectivity suggests that the simulated convective actions within TC outer spiral rainbands in Exp CTL are much more active than those in WRFBogus, especially in the northwest quadrant of TC vortex which is just the TC moving direction. The development of these deep convections is induced by the interaction between the warm and moist southwesterly flow on the west side of the subtropical anticyclone and the TC outer core circulation, which is simulated by WRFBogus. The wind speed in TC’s northwest quadrant is strengthened due to the prevailing convections within the TC outer spiral rainbands in Exp CTL (Fig. 11), which intensifies the cyclonic secondary circulation on the north portion of the lower-level TC vortex. According to the beta-drifting theory (Wang and Holland, 1996a, b), the cyclonic circulation on the north side of lower-level TC vortex can increase the westward vortical tendency of the vortex, forcing the TC to move westward. This is the main reason for the differences in TC track simulation among the WRF simulations (Fig. 8). From the above analysis, we note that the successful TC initialization is based on the reasonable representation of the interaction between TC vortex and environmental circulation, which favors the evolution of TC outer spiral rainbands and ultimately promotes the forecasting skill of TC track by modifying the TC secondary circulation.

6. Conclusions

We have presented a humidity nudging scheme for TC initialization, in which the
analysis of humidity is enhanced in the deep convection regions according to the FY2 observation of CTBT. The nudging scheme compares the brightness temperature from the CRTM with the FY2 observation, and modifies the model’s specific-humidity profile according to the observed deep-convection structure. During the humidity nudging procedure, the simulated TC intensifies rapidly, and the ultimate intensity of the bogus vortex is very close to the observation at the end of nudging. The improved spatial distribution of humidity can also modify the size of TC through convective actions and diabatic heating process (Hill and Lackmann, 2009). We also find that the RMW of TC is impacted by the distribution of diabatic heating source, which has been adjusted by the humidity nudging (Fig. 4).

Sensitivity tests are performed to investigate TC vortex’s response to different humidity forcing within the deep-convection regions. We show that the humidity forcing can affect the simulation of TC intensity through adjustment of TC outer spiral rainbands. Specifically, for weaker humidity forcing in the TC outer circulation, the development of spiral rainbands is inadequate and the intensifications of TC maximum wind speed and minimum SLP are slower during the nudging phase.

All three humidity nudging experiments can reasonably predict the convective systems in TC inner core and outer spiral rainbands, while Exp WRFBogus generated from the simple Rankin vortex shows almost no outer spiral rainbands. The dynamical and thermodynamical balances between the inserted TC vortex and the background circulation could be obtained much likely in the humidity nudging experiments than in WRFBogus. The distribution of intensive wind around TC eyewall, the TC warm-core structure, and the SLP show consistency to the initial condition, which develops stably in intensity and coverage during the simulation. The TC outer spiral rainbands strengthened by the humidity nudging modify the asymmetric distribution
of TC wind field, which then impacts the TC track prediction through the interaction between TC vortex and environmental circulation while modifying the TC secondary circulation.

The humidity nudging initialization scheme can be used into real-time operational TC forecast to improve the TC intensity and structure prediction skill. But its impacts still need to be tested with more real TC cases studies. This paper is just the first step of series studies using the humidity nudging scheme, and more sensitivity studies will be carried out to improve its algorithm and coefficients. Instead of using the simple vortex inserting technique, future improvements of TC initialization procedure include using possible combination of Ensemble Kalman Filter (EnKF) technique (Chen and Syder, 2007; Wu et al., 2010), variational technique (Ma et al., 2006; Ma and Tan, 2010), and more observational data (i.e., TRMM rain rate, satellite surface winds, etc.).

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References


Table 1. Sensitivity experiments used to understand humidity nudging effect

<table>
<thead>
<tr>
<th>Exp name</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>CTL</td>
<td>if simulated CTBT &gt; observed CTBT, $\varepsilon = 1$, else $\varepsilon = 0.25$</td>
</tr>
<tr>
<td>Exp 1</td>
<td>if simulated CTBT &gt; observed CTBT, $\varepsilon = 1$, else $\varepsilon = 0.5$</td>
</tr>
<tr>
<td>Exp 2</td>
<td>if simulated CTBT &gt; observed CTBT, $\varepsilon = 1$, else $\varepsilon = 0$</td>
</tr>
<tr>
<td>Exp 00</td>
<td>$\varepsilon = 0$</td>
</tr>
</tbody>
</table>
Fig. 1 WRF model domains and storm locations of TC Khanun (2005) from 0000 UTC 8 September to 1200 UTC 11 September. The grid resolutions of domain 1 (D1) and domain 2 (D2) are 12 and 3 km, respectively.

Fig. 2 Schematic illustration of the tropical cyclone initialization by enhancing the environmental humidity: Moisture profile is modified after comparing CTBT observed by the satellite with that derived by CRTM. Nudging is turned off when the sea level pressure difference between bogus vortex and target time (T=0 h, 00UTC 9 September) observation becomes less than 5 hPa. The bogus TC vortex is inserted into the model initial condition at T=0 h, and then a 72-h forecasting is carried out.

Fig. 3 CTBT (K) derived from the stationary satellite FY2 at 11 μm Channel (top) and calculated from the CRTM model at 10.7 μm (Chane14 of GOES12) (bottom). Period spanned from (a) to (d) and from (e) to (h) is 0500-2300 UTC 08 September at 6-hr time interval.

Fig. 4 (Left) azimuthal average of radial wind speed (contours; contour interval is 2 m s⁻¹, and negative values are indicated by dashed curves), superimposed with diabatic heating (≥1×10⁻³ K s⁻¹ is shaded, and interval is 2×10⁻³ K s⁻¹). (Right) tangential wind speed (solid contours; contour interval is 5 m s⁻¹), and temperature perturbation (dashed contours; contour interval is 2 K). (a) and (b): 12 h (T= -12 h); (c) and (d): 15 h (T= -9 h); (e) and (f): 18 h (T= -6 h); and (g) and (h): 24 h (T= 0 h) of the humidity nudging procedure.

Fig. 5 Geopotential height difference (solid contours; contour interval is 80 gpm) temperature difference (≥2 K is shaded, and interval is 2 K) and wind difference (barb; full barb is equivalent to 5 m s⁻¹) between Exp 00 and Exp CTL (T = 0 h) at (a) 850
Fig. 6 Model-derived 700-hPa radar reflectivity (shaded; dBZ), 10-m horizontal wind (barb; full barb is equivalent to 5 m s\(^{-1}\)), sea level pressure (thick black contour; contour interval is 8 hPa), and the isotach of 25.7 m s\(^{-1}\) (damage-forcing wind) at 10 m (blue contour) of Exp CTL (the first row), Exp 00 (the second row), Exp 1 (the third row), and Exp 2 (the fourth row) at 9 h (T= -15 h), 15 h (T= -9 h), 18 h (T= -6 h), and 21 h (T= -3 h) of humidity nudging.

Fig. 7 Time evolution of model-simulated minimum SLP (hPa; open symbols) and maximum wind speed at 10 m (m s\(^{-1}\); filled symbols) for Exp CTL (circles), Exp 1 (triangles) and Exp 2 (squares) calculated every hour from 6 h (T= -18 h) to 24 h (T= 0 h) of humidity nudging, The observed minimum SLP and maximum wind speed from JTWC are also indicated by star symbols.

Fig. 8 Simulated storm tracks of TC Khanun (2005): gray line with stars (Exp CTL); yellow line with arrowheads (Exp 1); pink line with crosses (Exp 2); blue line with squares (WRFBogus); red line with triangles (Exp 00); and black line with open circles for the best track observation from the JTWC.

Fig. 9 (a) Minimum SLP and (b) maximum 10-m wind speed for predictions of Khanun from T= 0 h to T= 60 h. Exp CTL, Exp 1, and Exp 2 are three humidity nudging simulations with different humidity forcing intensity; WRFBogus uses a simple TC bogus scheme in the WRF model, and Exp 00 does not implement any TC initialization procedure. The observation (Obs) is from the JTWC.

Fig. 10 Simulated sea level pressure (solid contour; contour interval is 10 hPa), stream line and wind speed (shaded) at T= 6 h for (a) Exp CTL at 850 hPa, (b) Exp CTL at 200 hPa, (c) WRFBogus at 850 hPa, and (d) WRFBogus at 200 hPa.

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second column), Exp 1 (the third column), and Exp 2 (the fourth column) at T = 6 h (top) and T = 30 h (bottom). Lines AB and CD indicate locations of the vertical cross-section in Fig. 13 and Fig. 14, respectively.

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