THE SPIN-UP PROCESS OF A CYCLONE VORTEX IN A TROPICAL CYCLONE INITIALIZATION SCHMEM AND ITS IMPACT ON THE INITIAL TC STRUCTURE

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1. Introduction

Nguyen and Chen (2011) (hereafter NC2011) developed a new dynamical tropical cyclone initialization method through model cycling runs. They hypothesize that the tropical cyclone structure is closely related to the environmental fields that the storm is embedded in. The typhoon structure is spun up by a high-resolution mesoscale model through a series of short-time (~1 h) cycling runs under given environmental conditions until it reaches or is close to the observed intensity from best track data. The NC2011 TC initialization scheme can produce an asymmetric structure of Typhoon Morakot (2009) over the open ocean that is consistent with satellite data. NC2011 compared model results from three different initial conditions to simulate Typhoon Morakot, namely, the initialization using data from the National Centers for Environmental Prediction (NCEP) Global Forecast System (GFS), the Weather Research and Forecasting-Advanced Research WRF (WRF-ARW) model's bogus scheme, and their own scheme. With better initial storm intensity and structure at the model initial time, their scheme's performance in simulating Typhoon Morakot's track and intensity is superior to the other two experiments. With more realistic TC structure at the model initial time than the other two methods, the model can better simulate rainfall patterns over the open ocean as well as after making landfall, consistent with radar and rain gauge observations. In addition to Typhoon Morakot, they also applied their scheme to Typhoon Jangmi (2008) and Kalmaegi (2008). For all cases considered, the NC2011 scheme provides better track and intensity simulations for typhoons with better storm structure and rainfall patterns than the other two experiments. This is mainly because the initial storm intensity and structure are better adjusted to the environmental conditions in which they are embedded and well adapted to the model employed.

NC2011 suggests that the asymmetric structure of Typhoon Morakot with rainbands and convective activity extending from the southeastern quadrat of the eyewall southwestward ("9" type structure) over the open ocean is related to the moisture transport by the southwesterly monsoon flow and the convergence between the southwesterly monsoon flow and the storm circulation. Some of the late summer/early-autumn cases are under the northeasterly monsoon flow with rainbands and extensive convective activity extending northeasterward ("6" type structure). During the mature stage, some also storms undergo an eyewall replacement cycle (Yang et al., 2013). We examine a few storms for all three types of structure in this study. Are the differences in the storm structure related to the differences in the environmental conditions in which these storms are embedded? Is the initialization technique proposed by NC2011 capable of producing realistic structure of a tropical cyclone at model initial time for all three types of storm structure? The primary goal of this study is to determine to what extent the NC2011 scheme can reproduce initial TC structure under different environmental settings.

2. Model Setup and Vortex Spin-up Scheme

The global gridded data were used as the initial conditions for the vortex spin-up process through a series of 1-h cycling runs. For each cycling run, the TC vortex from the previous 1-h run was separated from its environmental conditions and brought back to its observed location for next 1-h cycling run with the environmental conditions unchanged until its intensity is close to the best track data. The WRF-ARW model v3.3.1 is used. There are two domains with 121x121, 205x205 grid points and 38 vertical levels for the 18-km and 6-km domains, respectively. The WSM6 cloud microphysics (Hong and Lim, 2006), Grell's

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cumulus parameterization (Grell, 1993), Rapid Radiative Transfer Model long-wave radiation parameterization (Mlawer et al., 1997), Duhia's shortwave short radiation (Dudhia, 1989), and Yonsei University's boundary layer parameterization (Hong and Pan, 1996) are employed. For the 2004-2006 cases, we use the NCEP Final Analysis (FNL) 1.0-degree data. For the cases after 2007, we use the NCEP GFS data with a 0.5-degree grid. The microwave satellite observations of typhoons are compared with simulated initial typhoon structure because

Name of TC	Spin-up Time	TC Structure Type
Dujuan	1200 UTC 31 Aug. 2003	9
Nakri	0000 UTC 31 May 2008	9
Morakot	0000 UTC 06 Aug. 2009	9
Muifa	0000 UTC 31 Jul. 2011	9
Vicente	0000 UTC 22 Jul. 2012	9
Jelawat	0000 UTC 23 Sep. 2012	9
Soulik	0000 UTC 11 Jul. 2013	9
Trami	0000 UTC 20 Aug. 2013	9
Haiyan	0600 UTC 05 Nov. 2013	9 (special)
Mitag	1200 UTC 22 Nov. 2007	6
Tembin	1200 UTC 20 Aug. 2012	6 (special)
Fitow	1200 UTC 05 Oct. 2013	6
Lekima	1800 UTC 21 Oct 2013	6
Krosa	0000 UTC 02 Nov. 2013	6
Fransico	0600 UTC 22 Oct. 2013	CE
Chaba	0600 UTC 27 Aug. 2004	CE
Dianmu	1200 UTC 18 Jun. 2004	CE
Chanchu	0000 UTC 16 May 2006	CE

microwave radiation can penetrate clouds in all weather conditions to delineate typhoon structures, such as spiral rain bands, vortex circulation, tropical cyclone double eye-wall. In this paper, three recent examples with "9" type (Soulik, 2013), "6" type (Fitow, 2013), and concentrated eyewall (Chanchu, 2006), respectively, are presented to show the capability of the NC2011 scheme.

Table 1. All selected cases from 2004-2013 with NC2011 typhoon initialization scheme. The first column is the name of TC. The second column is the spin-up time, and the final column is the TC structure type. "CE" denotes concentrate eyewall.

3. Results and discussion

(a) "9" type tropical cyclone structure

For the "9" type of tropical cyclone, we selected Typhoon Soulik (2013). The predecessor of the TC is a mid- to upper-level low about 1,400 km northeast of Guam on 5 July 2013. Typhoon Soulik (2013) formed and was named about 620 km north of Guam at 0000 UTC 8 July 2013. After its formation, TC Soulik continued to move westward with increasing intensity. At 0000 UTC 10 July 2013, Typhoon Soulik reached maximum intensity with a minimum pressure around 925 hPa about 1000 km southeast of Okinawa. At 0000 UTC, 11 July Typhoon Soulik exhibited asymmetric structure (Fig. 1a).

The simulated radar reflectivity for Typhoon Soulik exhibits asymmetric structure (Fig. 1b) consistent with microwave satellite observations (Fig. 1a). The convection was suppressed in the northwest/western part of the typhoon. In the eastern part of typhoon, the maximum wind speed was 50 m s^{-1} along the eyewall tilts and extended above 5 km with extensive convection. On the western side of typhoon, however, the maximum wind speed of 50 m s^{-1} along the eyewall is confined to a small area below the 1-km level with relatively weak convective activity (Fig. 1c). In the northern part of typhoon, the maximum wind speed is 50 m s^{-1} and extends above 4 km. On the southern/southeastern side of typhoon, which is on the downshear side with abundant moisture, the convective activities are very active (Figs. 1c and 1d).

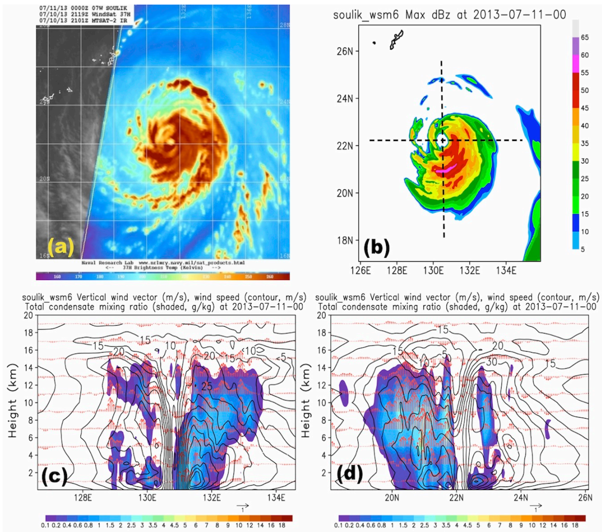

Figure 1 Typhoon Soulik's structure at 0000 UTC, 11 Jul 2013: (a) The WindSat 37 GHz brightness temperature (degree Kelvin); (b) simulated radar reflectivity (dBz). The dash lines indicate the East-West (EW) and North-South (NS) cross sections, (c) The EW cross section across the TC center. Wind speed (contour, m s^{-1}), vertical wind (vector, m s^{-1}), total condensate mixing ratio (shaded, g/kg). (d) same as (c), but for the NS cross section.

(b) "6" type typhoon structure

This type of storm usually occurs in the late season in autumn or early winter after the onset of the northeasterly monsoon flow. In this study, we examine the initial storm structure of Typhoon Fitow from NC2011's initialization scheme. On 26 September 2013, a tropical low-pressure system formed near Palau. On 30 September, it developed into Typhoon Fitow (2013) and reached its maximum intensity with a minimum central pressure ~960 hPa at 2100 UTC 4 October 2013.

From satellite observations (Fig. 2a), the TC exhibited an asymmetric structure with a spiral rainband extending from the northwestern quadrat northeastward. The initial storm structure in the model using the NC2011 technique (Fig. 2b) is consistent with satellite observations (Fig. 2a). Along the East-West cross section (Fig. 2c), the convection activity outside the eyewall is weak. From the north-south cross section (Fig. 2d), the asymmetric storm structure with stronger tangential winds on the northern side and extensive convective activity associated with the northern spiral rainband is evident (Fig. 2d).

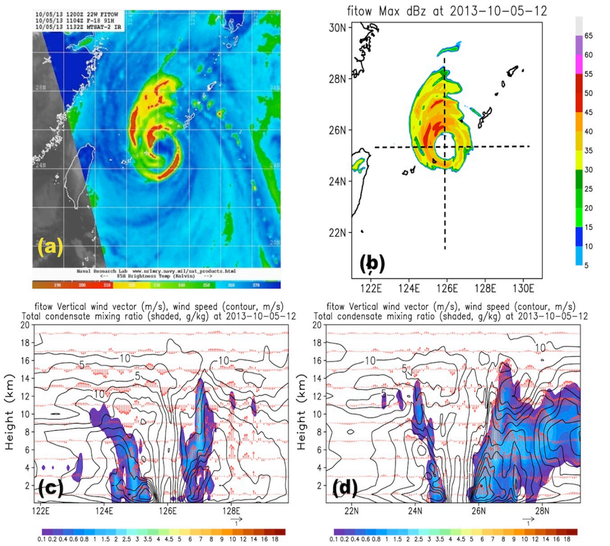

Figure 2. Typhoon Fitow's structure at 1200 UTC 5 October 2013: (a) The SSMI/S 85 GHz brightness temperature (degree Kelvin). (b) simulated radar reflectivity (dBz). The dash lines indicate the East-West (EW) and North-South (NS) cross sections, (c) The EW cross section across the TC center. Wind speed (contour, m s^{-1}), vertical wind (vector, m s^{-1}), total condensate mixing ratio (shaded, g/kg). (d) same as (c), but for the NS cross section.

(c) The concentric eyewall structure

Typhoon Chanchu (2006) formed as a tropical depression on 9 May, 2006 at about 8.3°N, 133.4°E. It made landfall over the Philippines on late 11 May, 2006. After Typhoon Chanchu moved westward and crossed the Philippines, it intensified into a super typhoon with a minimum central pressure of ~920 hPa at 0000 UTC 15 May, 2006 and underwent an eyewall replacement cycle during 15-16 May. Typhoon Chanchu occurred after the onset of the southwesterly monsoon over IndoChina with a moisture tongue associated with the southwesterly flow off the southern Vietnam coast extending northeastward off the northwestern Philippines coast.

Satellite observations show that Typhoon Chanchu has a double eyewall at 0000 UTC 16 May, 2006 with a symmetric structure (Fig. 3a). The simulated radar reflectivity structure of Typhoon Chanchu (Fig. 3b) shows the existence of both the inner and outer eyewall structures with a spiral outer rainband, consistent with satellite observations. Both the East-West and North-South cross sections through the TC center (Figs. 3c and 3d) also clearly show the double eye wall structure with a much weaker wind speed associated with the outer eyewall. The TC axisymmetric structure is evident from both the horizontal distribution and vertical cross sections (Figs. 6c and 3d). It is apparent that the NC2011scheme is capable of reproducing the observed concentrate eyewall structure after the storm reached the maximum intensity.

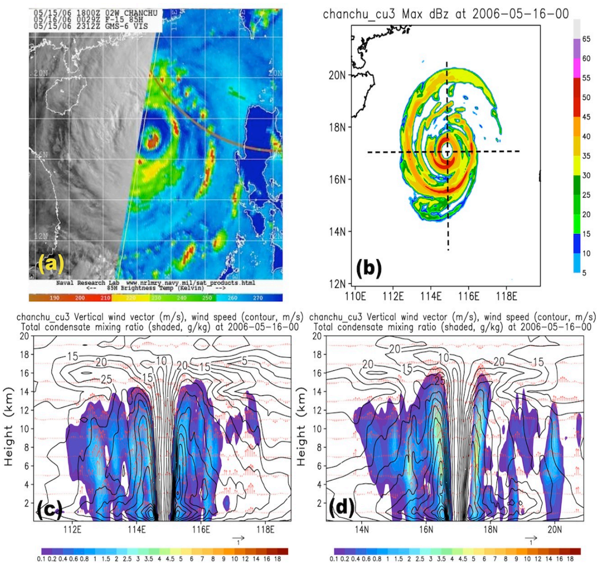

Figure 3. Same as Fig. 4 but for Typhoon Chanchu at 0000 UTC 16 May 2006.

In addition to the above three examples, we also use the same scheme to spin up other typhoons that occurred in the Western Pacific during 2004-2013 including: Dujuan (2003); Chaba (2004); Dianmu (2004); Chanchu (2006); Mitag (2007); Nakri (2008); Morakot (2009); Muifa (2011); Jelawat (2012); Tembin (2012); Vicente (2012); Krosa (2013); Francisco (2013); Haiyan (2013); Lekima (2013); and Trami (2013) (Table 1). For cases embedded in the summer southwesterly monsoon flow with the "9" type asymmetric structure (Dujuan, Nakri, Morakot, Muifa, Jelawat, Vicente, and Trami), the storm structure is reproduced by this scheme. Similarly, cases showing the "6" type structure embedded in the northeasterly monsoon flow (Mitag, Francisco, Lekima, and Krosa) are also successfully spun up in the model with a similar asymmetric storm structure. Typhoon Tembin (2012) occurs in late summer but still exhibits a "6" type structure due to the presence of an upper-level cold core to the northwest. Typhoon Haiyan (2013) is a wintertime case, but it occurs in low latitude under the southwesterly flow and still exhibits a "9" type structure. There are cases (Chaba, Dianmu, Chanchu, and Francisco) that feature eyewall replacement during part of their lifetime. For all the cases considered, our scheme performs reasonably well in duplicating the initial storm structure in the model.

4. Conclusion

Typhoon structure is affected by the environment flow in which it is embedded and the NC2011 scheme has considerable skill in reproducing the observed structure in the model initial conditions based on the given large-scale conditions in which the storm is embedded.

Over the Northwest Pacific, tropical cyclones can occur either under the summer southwesterly (SW) monsoon or the northeasterly (NE) monsoon for the late season cases. Under the summer SW monsoon, typhoons have a tendency to exhibit a "9" type structure with more extensive spiral rainbands extending from the east/southeastern side of the storm southwestward than their northern counterparts (Fig 1a). At low levels, the warm, moist southwesterly flow converges with the cyclonic storm circulation to the south of storm center. With the SW monsoon flow in low levels and equatorial easterlies aloft, the deep layer wind shear (upper-level winds–low-levels winds) tends to be northeasterly. Under the late season northeasterly monsoon flow, these storms frequently exhibit a "6" type structure with more extensive convection and rainbands extending from the north/northwestern part of the storm center northeastward than its southern counterpart. For these late season storms, the TCs are often affected by the mid-latitude frontal systems with southwesterly flow aloft whereas the low-level flow is dominated by the NE monsoon flow. The low-level cyclonic storm circulation converges with the NE monsoon flow north/northwest of the storm center with upper-level outflow channel pointing northeastward. It has been shown that the NC2011 TC initialization technique is capable of reproducing both types of asymmetric storm structure.

Some intense storms may undergo eyewall replacement during part of their life cycle, especially during the mature stage, under favorable large-scale settings. These settings include weak shear with symmetric upper-level outflow channels both south and north of the storm center. The NC2011 scheme also shows considerable skill in reproducing the concentric eyewall structure.

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