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Mesoscale model predictions of typhoon structure and motion in the western Pacific during October 2004

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1. Introduction

Tropical cyclones pose a major threat to coastal life and property. Numerical prediction of tropical cyclones has improved enormously over the past few decades. However, since most of their life cycles reside over the data sparse oceanic regions, the advancements in the tropical cyclone initialization are rather slow and accurate prediction of their tracks and intensity changes has remained a challenging task for the forecasting community (Leslie and Holland 1995; Elsberry 1995). Tropical cyclone/typhoon initialization commonly employs a vortex bogussing technique to insert a more realistic typhoon structure into the reanalysis. Following gradient-wind relations, the bogus vortices are specified by the maximum tangential wind speeds, the radial distance at which the maximum winds occur, and a shape factor based on the size of the vortex (Holland 1980; Kurihara *et al.* 1993; Chan and Williams 1987; Fiorino and Elsberry 1989). An *ad hoc* balancing procedure is applied using geostrophic relations, non-linear balance methods, etc. to construct the kinematic and thermodynamic structure of the typhoons. Although various bogus methods are employed in the numerical weather prediction (NWP) of typhoons, the understanding is that they do not always lead to efficient track predictions (Wang 1998).

The challenges in tropical cyclone predictions are not only from the vortex initialization, but also from accurate representation of the large-scale analyses in which it is embedded, and deficiencies in the physical parameterizations used in the NWP models, and model parameters such as the grid resolution to resolve the convective motions in typhoons. In this study, we assess the impact of vortex initialization bogussed into the global National Center for Environmental Prediction (NCEP) reanalysis fields on the accuracy of typhoon tracks.

2. Supertyphoon Ma-on

In this study, one of the powerful typhoons of the century, Supertyphoon Ma-on in the western Pacific Ocean that made the landfall in Japan during 3-10 October 2004, is investigated. The synoptic history of Ma-on showed that a trough exiting the east coast of China favored its poleward movement heading towards Japan. The trajectory of the typhoon is shown in Fig. 1.

Supertyphoon Ma-on (26W) originated as a weak low level circulation centered 130 km north-northwest of Guam on 29 September 2004. After days of remaining as a weak low level circulation across the western Pacific, Ma-on intensified to a tropical storm on 5 October, and reached category 1 [maximum sustained winds of 33-43 m s^{-1}, category described as a minimal typhoon] on the 6th at 1200 UTC, with its center located 760 km southeast of Okinawa, Japan. It rapidly intensified to category 5 [maximum sustained winds 70-87 m s^{-1}, category described as a devastating typhoon] moving northeastward in a span of 24 hours. The central pressure was 920 hPa on 8 October 2004 at its mature stage. Ma-on made landfall on the Izu peninsula, Honshu, Japan, on the 9th at 0700 UTC with a maximum sustained winds of 50 m s^{-1}. The storm system had completed its transformation to an extra tropical system at 1800 UTC and further moved east-northeastward. The lifetime of the typhoon was about 6 days with a length of movement of about 3600 km.

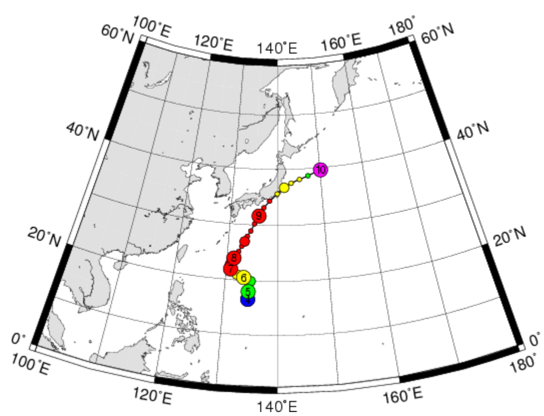

Fig.1 Track of Supertyphoon Ma-on during 4-10 October 2004 (source: http://agora.ex.nil.ac.jp).

3. Model Description and Vortex Initialization

The fifth-generation Penn State/NCAR Mesoscale Model (MM5; Grell *et al.* 1995) has been widely used to study the impact of vortex initialization in recent years (Xiao *et al.* 2000; Davis and Low-Nam 2001). The default MM5 preprocessing procedure for vortex bogussing employs Rankine-type vortices (Milne-Thompson 1968; Trinh and Krishnamurti 1992). In this study, we configured MM5 using two domains with horizontal grid resolutions of 27 and 9 km and 41 vertical levels. The preliminary study focuses on the impact of vortex initialization on the position errors using a lagged averaged forecasting method (Hoffman and Kalnay 1983; Elsberry *et al.* 1991). Nine forecasts were created starting from 6 October 2004 and lagged by 6 hours to assess the 12-72 h position errors in the typhoon track.

An axially symmetric vortex centered at the best track positions issued by the Joint Typhoon Warning Center (JTWC) is bogussed into the National Center for Environmental Prediction (NCEP) 1° × 1° global reanalysis fields at every lagged MM5 initialization. The following analytical tangential wind profile, following Chan and Williams (1987) and Fiorino and Elsberry (1989), is used in this study and is given as follows:

$$V(r,p) = W(p)\, V_m \left(\frac{r}{r_m}\right)\, exp\left\{\left(\frac{1}{b}\right)\left(1-\left[\frac{r}{r_m}\right]^b\right)\right\} \quad \text{------- (1)}$$

where V is the tangential wind speed as a function of radial distance r, V_m is the intensity or maximum wind speed that occurs at a radial distance r_m from the center of the typhoon. r_m is assumed to be 90 km, and b governs the shape of the tangential wind velocity profile and is iteratively determined by assuming V(r=400 km) is 15 m s^{-1}. The shape factors ranged between 0.6 and 0.8 in the present study. W(p) is a weighting function in pressure p, 1 from surface through 850 hPa, 0.95 at 700 hPa, 0.9 at 500 hPa, 0.7 at 300 hPa, 0.6 at 200 hPa, and 0.1 at 100 hPa, specified to obtain the vertical structure of the bogus vortex.

4. Results and Discussions

MM5 Initialization using axially symmetric vortices following Eq. (1) produces better evolution of the vortex structure and intensity. The sea-level pressure with a bogus vortex imposed into the NCEP

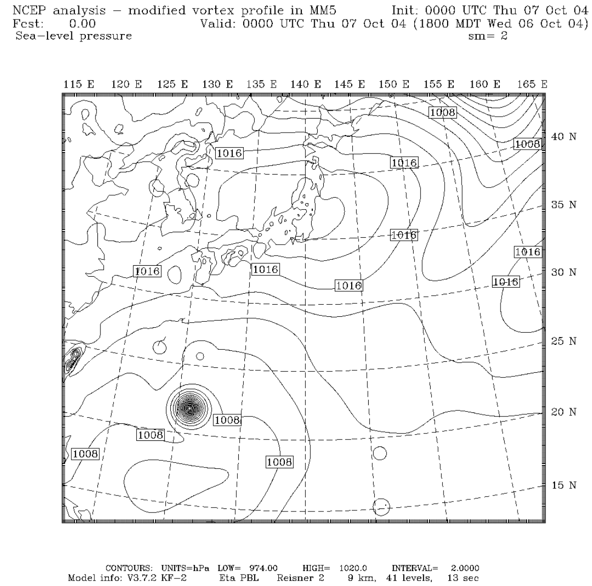

Figure 2. Sea-level pressure (NCEP reanalysis + bogus vortex) on 7 October 2004 at 00 UTC. The typhoon central pressure is 974 hPa.

reanalysis field used for one of the model simulations initialized on 7 October 2004 at 00 UTC is shown in Fig. 2, and its evolution after 24 and 48-hours is shown in figures 3 and 4. The simulated pressure drop at the typhoon center was approximately 12 hPa in 24 hours and the pressure drop is more pronounced in the simulations with longer lead time (see Fig 6). The typhoons simulated after 8 October 2004 showed predominantly northward propagation and did not recurve significantly as observed (Figs 1 and. 6).

The simulated mean position errors using the lagged average forecast method compared to the JTWC documented storm positions for the nine simulations initialized at different synoptic hours are listed in Table 1. It can be seen that the position errors were considerably smaller while the storm was predominantly over the ocean and the typhoon path errors are significantly large while the storm was heading towards Japan. The large errors in the positions and the environmental steering can be attributed partly to the uncertainties in the large-scale flow in the initialization and simulated trough movement off the eastern China coast as can be seen in the mid-tropospheric flow in Fig. 5, and partly to the rigid assumptions used in the vortex parameters for initialization.

A preliminary MM5 investigation suggested that the vortex initialization into the NCEP-reanalysis using Rankine type vortices could not reproduce the vortex structure at a later time correctly due to

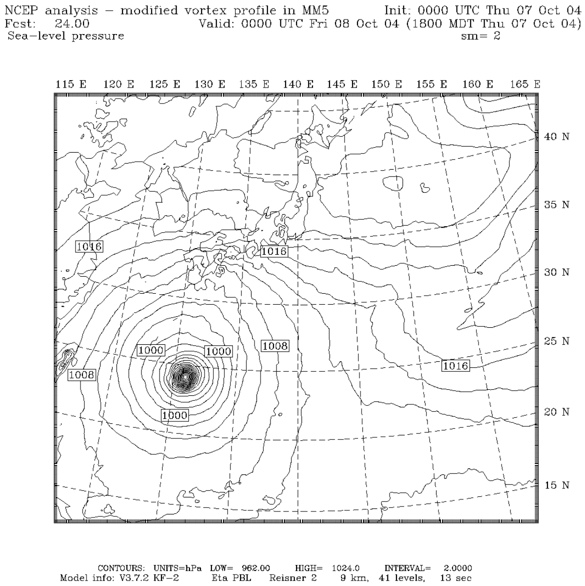

Figure 3. Forecasted (24-h) sea-level pressure on 8 October 2004 at 00 UTC. The typhoon central pressure is 962 hPa.

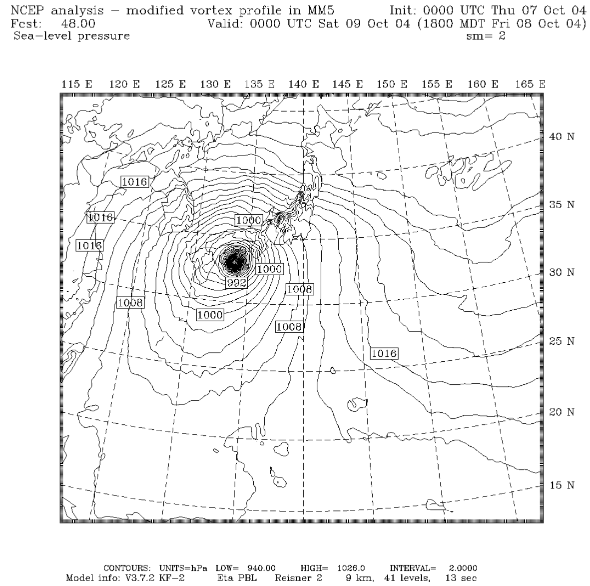

Figure 4. Same as in Fig. 3, but for 48-h forecast. The typhoon central pressure is 940 hPa.

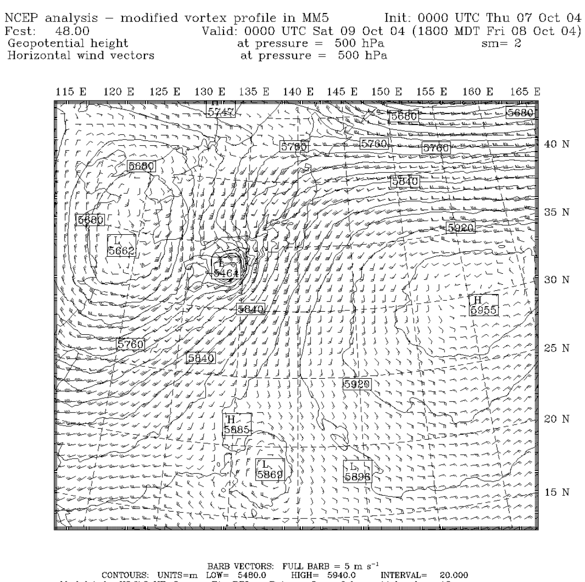

Figure 5. Same as in Fig. 4, but for 500-hPa winds (barbs) and geopotential heights (m).

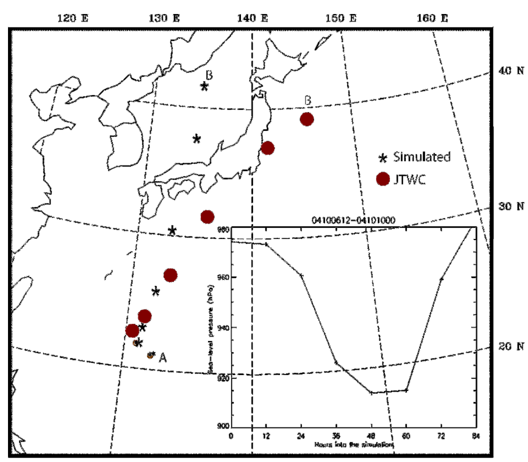

Figure 6. JTWC observed and MM5 simulated typhoon track at 12 hour intervals (inset: Sea-level pressure; hPa). MM5 initialized at 6 October 2004 at 12 UTC (position marked as A; B = 10 October 2004 at 00 UTC). Simulation period = 84 hours.

Table 1. Typhoon position errors (in km) obtained from 9-km model grid – MM5 Simulated .vs. JTWC.

MM5 initialization Time = 0 h	12 h forecast	24 h forecast	36 h forecast	48 h forecast	60 h forecast	72 h forecast
6 Oct 04 12 UTC	102	120	107	415	322	598
6 Oct 04 18 UTC	76	57	87	167	351	808
7 Oct 04 00 UTC	102	122	259	358	598	888
7 Oct 04 06 UTC	122	301	462	614	951	
7 Oct 04 12 UTC	189	640	612	1047	1464	
7 Oct 04 18 UTC	260	588	827	1132		
8 Oct 04 00 UTC	469	734	1190	1323		
8 Oct 04 06 UTC	477	991	1269			
8 Oct 04 12 UTC	580	897	726			
Mean (km) No. of forecasts	264 9	494 9	615 9	722 7	737 5	764 3

rapid weakening of the typhoon system. The present study demonstrates the feasibility of applying a shape defined wind profile into MM5 initialization for better results. An estimation of the impact of uncertainties in the vortex parameters and in the large scale flow on the vortex motion and strength is presently underway.

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