Impact of bogus vortex for track and intensity prediction of tropical cyclone

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The initialization scheme designed to improve the representation of a tropical cyclone in the initial condition is tested during Orissa super cyclone (1999) over Bay of Bengal using the fifth-generation Pennsylvania State University – National Center for Atmospheric Research (Penn State – NCAR) Mesoscale Model (MM5). A series of numerical experiments are conducted to generate initial vortices by assimilating the bogus wind information into MM5. Wind speed and location of the tropical cyclone obtained from best track data are used to define maximum wind speed, and centre of the storm respectively, in the initial vortex. The initialization scheme produced an initial vortex that was well adapted to the forecast model and was much more realistic in size and intensity than the storm structure obtained from the NCEP analysis. Using this scheme, the 24-h, 48-h, and 72-h forecast errors for this case was 63, 58, and 46 km, respectively, compared with 120, 335, and 550 km for the non-vortex initialized case starting from the NCEP global analysis. When bogus vortices are introduced into initial conditions, the significant improvements in the storm intensity predictions are also seen.

The impact of the vortex size on the structure of the initial vortex is also evaluated. We found that when the radius of maximum wind (RMW) of the specified vortex is smaller than that of which can be resolved by the model, the specified vortex is not well adapted by the model. In contrast, when the vortex is sufficiently large for it to be resolved on horizontal grid, but not so large to be unrealistic, more accurate storm structure is obtained.

1. Introduction

Forecast of track and intensity changes for mature tropical cyclones requires accurate representation of the tropical cyclone vortex in the model initial conditions. Vortices contained in the large-scale analyses from operational centers are often too broad and too weak and sometimes misplaced because observations in the vicinity of the tropical cyclones are usually sparse. In order to improve the storm representation, the use of so-called bogus vortices is often adopted (Kurihara *et al* 1990; Lord 1991; Leslie and Holland 1995). Many successful simulations, including prediction of hurricane movement and structure, have been conducted using bogus vortices for hurricane model initialization (e.g., Kurihara *et al* 1990; Lord 1991; Trinh and Krishnamurti 1992). Although bogussing schemes are employed by many NWP centers, they do not always work well for a large range of tropical cyclones (Wang 1998). However, an important issue in such an approach is the consistency of the vortex with the properties of the prediction model (Iwasaki *et al* 1987; Mathur 1991).

In the GFDL bogussing scheme (Kurihara *et al* 1993) a sophisticated filtering is used to overcome such defects. The main strategy of their scheme is to change the poorly resolved vortex from a coarse-resolution analysis to a more realistic vortex that is constructed to better match the high-resolution

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hurricane prediction model. As anticipated, the method shows a substantial improvement in the track prediction (Bender *et al* 1993).

In the recent work of Zou and Xiao (2000), a variational bogus data assimilation (4DVAR) scheme was proposed to generate the structure of a tropical cyclone in the initial condition of a high-resolution mesoscale model. The method requires two-steps:

- specification of a bogus vortex by defining the position, radius of maximum surface wind (RMW), and minimum sea levels pressure (SLP) of initial vortex, and prescribing a symmetric SLP distribution over the vortex regions; and
- assuming that time tendency of SLP is small in a short time period and then assimilating the specified bogus SLP field into the numerical model within a 30 min assimilating window. They show very encouraging results for Hurricane Felix (1995).

Xiao *et al* (2000) applied the 4DVAR bogussing technique to Hurricane Fran (1996) and examined the impact of the specified vortex size and the relative impact of the bogus SLP and wind data. The initial vortex size affected both the track and intensity of the assimilated hurricane, with larger vortices generally moving somewhat to the left of smaller vortices and having weaker intensity. According to their results, Xiao *et al* (2000) concluded that the wind information had relatively small impact.

Recently, Zhao and Braun (2001) examined the effectiveness of the four-dimensional variational assimilation techniques for creating bogus vortices in numerical simulation of hurricanes using MM5 and its adjoint system. The variational bogus vortex assimilation methodology was applied to the simulations of Atlantic hurricanes during 1998, by assimilation of bogus wind and SLP. They concluded that wind information had substantial impact. They suggested potential for improving the model initial condition and forecast of hurricane track and intensity by using satellite-sensed wind such as those derived from scatterometer (e.g., QuikSCAT satellite).

In order to further explore the effectiveness of the bogussing technique, this study examines the impact of wind information by applying the bogussing technique of Christopher *et al* (2001) to the Orissa super cyclone over Bay of Bengal in the year 1999.

2. Model description and vortex initialization scheme

2.1 *Model description*

The Pennsylvania State University – National Center for Atmospheric Research (PSU–NCAR) mesoscale forecast model version 3.6 (MM5) and its bogus vortex scheme is used in this study. The MM5 is a limited area, non-hydrostatic primitive equation model with multiple options for various physical parameterization schemes (Dudhia 1993; Grell *et al* 1995). This non-hydrostatic version employs reference pressure as basis for terrain – following vertical coordinate and the fully compressible system of equations. In combination with multiple-nest capability, a four-dimensional data assimilation technique and a variety of physics options, make the model capable of simulation on any scale, limited only by data resolution, quality and computer resources. Physics options used in this study include the Kain Fritsch cumulus (Kain and Fritsch 1993) parameterization, a simple-ice microphysics scheme (Dudhia 1993). Boundary layer was parameterized using the non-local scheme (Hong and Pan 1996), and a cloud radiation scheme of Dudhia (1989) is used. The land surface temperature is predicted using surface energy budget equations as described in Grell *et al* (1995).

2.2 *Vortex initialization scheme*

Because most of the first guess information that is available (and the models producing the information) is integrated on domains with relatively coarse effective resolution, the vortices contained in gridded analyses are too broad and too weak. Initialization of a higher-resolution model from these analyses results in a storm that typically maintains its physical characteristics from the initial time. If the storm starts out with a radius of maximum wind (RMW) of, say, 200 km, the RMW tends to remain near this value for an extended period during the forecast until the model is able to produce a scale contraction and associated intensification of the vortex. This often requires 1–2 days of integration. To improve the intensity prediction, it is necessary to insert an initial vortex that is closer to the observed storm intensity than is the vortex in the background. In order to do this, the erroneously large vortex in the background must be first removed. Otherwise, the initial state for MM5 would contain two vortices, which may be at different spatial locations.

The first step of the removal process is to identify the vortex corresponding to the storm of interest in the first guess field. This is accomplished by searching for the maximum vorticity on the analysis pressure-level nearest to the surface (either 1013 mb or 1000 mb) within a prescribed radial distance from the best track location of the tropical cyclone, this location serves as the center of the vortex to be removed. Because the first guess has a coarse grid increment, the vorticity field on the MM5 grid has no small-scale variations that might complicate locating the center. Once the first-guess vortex is located, there are many ways one might consider for removing it. For example, a scale-selective smoothing might be imposed to try to damp out the incorrect circulation. In the GFDL bogussing scheme (Kurihara *et al* 1993) a sophisticated filtering is used. However, smoothing can have adverse effects on the far field, and may not remove the entire storm from the first guess, or will likely leave significant imbalances in the modified background field. The NCAR–AFWA (Christopher *et al* 2001) tropical cyclone bogussing scheme modifies the vorticity, geostrophic vorticity, and divergence, then solves for the change in the non-divergent stream function, geopotential and velocity potential, respectively, and computes a modified velocity field.

The general approach to modifying the flow can be illustrated in the context of vorticity and non-divergent wind. The relationship between wind, stream function and vorticity is:

$$\nabla^2\psi = \zeta, \tag{1}$$

$$V_\psi = \hat{\kappa} \times \nabla\psi, \tag{2}$$

where ψ is the stream function for the non-divergent wind, ζ is the relative vorticity and V_ψ is the non-divergent wind. To define the non-divergent wind associated with the first guess storm, vorticity equal to zero is assigned outside a radius 'r_m', specify $\psi = 0$ on the lateral boundaries of the domain and solve equation (1) for a perturbation stream function ψ on all pressure surfaces. V_ψ is calculated from equation (2) and subtracted from the first-guess wind field.

Removal of divergent wind and pressure anomalies associated with the first-guess storm follows equation (1) and equation (2), except in the case of divergence, equation (1) and equation (2) are replaced by

$$\nabla^2\chi = \delta, \tag{3}$$

$$V_\chi = \nabla\chi, \tag{4}$$

where χ is the velocity potential, δ the divergence and V_χ is the divergent wind. To remove the geopotential height anomaly equation (1) and equation (2) become

$$\nabla^2\phi = \zeta_g f_0, \tag{5}$$

$$V_g = \hat{\kappa} \times \nabla\phi. \tag{6}$$

The geostrophic vorticity (ζ_g) is set equal to zero outside $r = r_m$, (5), (6), and (7) are solved for a geopotential anomaly ϕ to be subtracted from the background. To remove the temperature anomaly field due to the first-guess storm, the hydrostatic relation (equation 7) is used

$$\frac{\partial\phi'}{\partial \ln(p)} = -RT', \tag{7}$$

where R is the gas constant and p is the pressure. The temperature anomaly field is also removed, leaving a first guess field with only a background flow where the first guess storm was located.

Because the input data of Christopher *et al* (2001) scheme is limited, consisting mainly of storm location and estimated maximum winds, the specification of a three-dimensional vortex structure is arbitrary, to some extent. The need for rapid integration of the model initialization scheme precludes the use of sophisticated schemes such as developed by Zou and Xiao (2000) based on four-dimensional, variational data assimilation (4D-VAR).

The vortex wind profile is given by the simple Rankine vortex:

$$V = \dot{A}(z)F(r), \tag{8}$$

$$F(r) = \frac{v_m}{r_m} r \qquad (r \le r_m), \tag{9}$$

$$F(r) = \frac{v_m}{r_m^\alpha} r^\alpha \qquad (r > r_m), \tag{10}$$

where v_m is the maximum tangential wind at radius of maximum wind, r_m, α is constant and assigned a value of -0.75 suggested by Christopher *et al* (2001). Other studies suggest a slightly different typical value of around -0.5 (Riehl 1963). However, these profiles tend to be measured only within ~ 150 km of the storm center. Such a profile yields velocities that are demonstrably too large at large radii (of order 500–1000 km) where the influence of the hurricane flow is often hard to deduce given the presence of other disturbances. The choice of $\alpha = -0.75$ is a compromise to yield an approximately correct functional relationship near the storm and reduce the influence of the storm at large radii.

The amplitude and height dependence are contained in $A(z)$. We assume that the maximum azimuthally averaged wind is $0.75\,V$, where V is the reported maximum wind from the Best Track data. The coefficient 0.75 is based on several MM5 simulations of tropical cyclones of varying intensities with varying grid increments. The vertical weight function is specified to be unity from the surface through 850 mb, 0.95 at 700 mb, 0.9 at 500 mb, 0.7 at 300 mb, 0.6 at 200 mb and 0.1 at 100 mb.

3. Evaluation of the bogus vortex scheme with Orissa super cyclone 1999

3.1 *Summary of Orissa super cyclone over Bay of Bengal (25th–31st October)*

It was the most intense tropical cyclone in the history of Orissa for the last 114 years since the False point cyclone of 19th–23rd September 1885. This state was battered for more than two days by its fierce winds and intense rain. It also produced a huge storm surge and catastrophic floods. The initial disturbance that eventually led to this development was discerned in the Gulf of Thailand on 24th October. While moving west–northwestward it intensified through several stages of evolution particularly on 28th October when it slowed down its forward motion. It crossed Orissa coast of India close to Paradip (20.45°N, 86.55°E) between 0430 and 0630 GMT of 29th October.

The initial vortex was spotted over Gulf of Thailand (figure 1) at 00 GMT on 24th October. Moving westward across Malaysian peninsula, it emerged in north Andaman Sea as a well-marked low-pressure area in the morning of 25th October. It concentrated into depression in the evening of the same day and was centred at lat. 13.5°N/lon. 98.0°E on 1200 GMT of 25th October. The depression moved in west–northwesterly direction and intensified into a cyclonic storm at 003 GMT of 26th October near lat. 13.5°N/lon. 95.0°E. The system was further intensified as a severe cyclonic storm at 003 GMT of 27th October near lat. 16.0°N/lon. 92.0°E. While continuing to move north–westwards it deepened further. At 003GMT of 28th October it was located near lat. 17.5°N/lon. 89.5°E. The system attained the stage of super cyclonic storm at 15 GMT of 28th October near lat. 19.0°N/lon. 87.5°E. After crossing coast the system tracked very slowly a little further to the northwest, weakened and lay centred at 12 GMT of 29th October near lat. 20.5°N/lon. 86.0°E. The storm caused exceptionally heavy rain (20 cm in 24 hours) over some stations in Orissa.

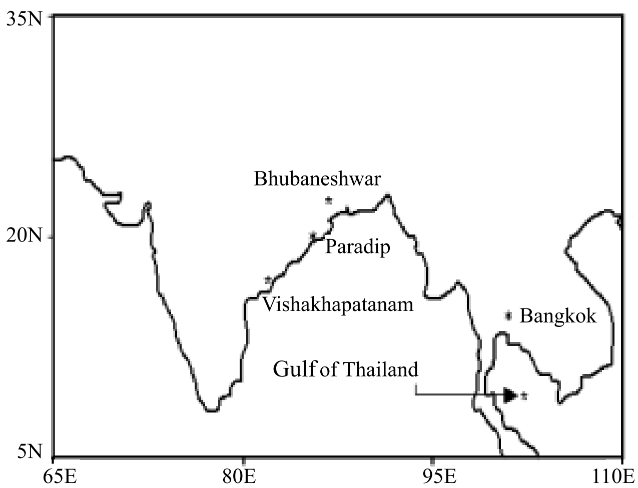

Figure 1. Locations used to describe the cyclone genesis and movement.

3.2 *Numerical simulation of Orissa super cyclone 1999*

3.2.1 *Model initial condition and experimental design*

The model was run with 45 km horizontal resolutions with a single domain. Twenty-nine unevenly spaced full-sigma levels were used in the vertical, with the maximum resolution in the boundary layer. Thirty minutes averaged terrain/landuse data were interpolated to 45-km model grids. Initial and boundary conditions for 45 km domain are derived from NCEP analysis archived at NCAR. Analysis fields including temperature, relative humidity, geopotential height, and winds at mandatory pressure levels with horizontal resolution of $2.5° \times 2.5°$, are interpolated horizontally to model grid points. The MM5 initial conditions derived from NCEP analysis are designated as the control analysis or 'NBOG analysis'. The MM5 initial conditions derived from NCEP analysis after putting bogus vortex are designated as experimental analysis or 'BOG analysis'. The bogussing is based on the observation of central location at 16.2°N and 92°E, a maximum surface wind speed of 30 m/s. The radius of maximum wind speed is also required, which is generally not available. Earlier some studies suggested that the values of RMW should be a function of model resolution. We tried with four values of RMW and based on this we prepared four (BOG45, BOG90, BOG135, and BOG180) BOG analyses based on different values (45 km, 90 km, 135 km, and 180 km) of radius of maximum wind (RMW).

Figure 2 shows the analysis for sea level pressure (SLP) and 850 mb wind field at 00 GMT of 27th October 1999, for NBOG (figure 2a) and BOG45 (figure 2b). At that time, tropical cyclone was a category 4 (i.e., severe cyclonic storm), but the NBOG analysis shows only a weak pressure minimum (about 1004 mb) and the centre of the storm (14°N, 91°E) is very much different from the observed (16°N, 92°E). The vortex in the case of BOG45 analysis is more intense (central pressure 993 mb) and better organized than the vortex in NBOG. Winds show a more realistic distribution and maximum winds occur closer to the vortex centre. Although a symmetric vortex structure is assimilated, the resulting wind speed distribution includes an asymmetric structure in the case of BOG45 analysis. The impact of the assimilation

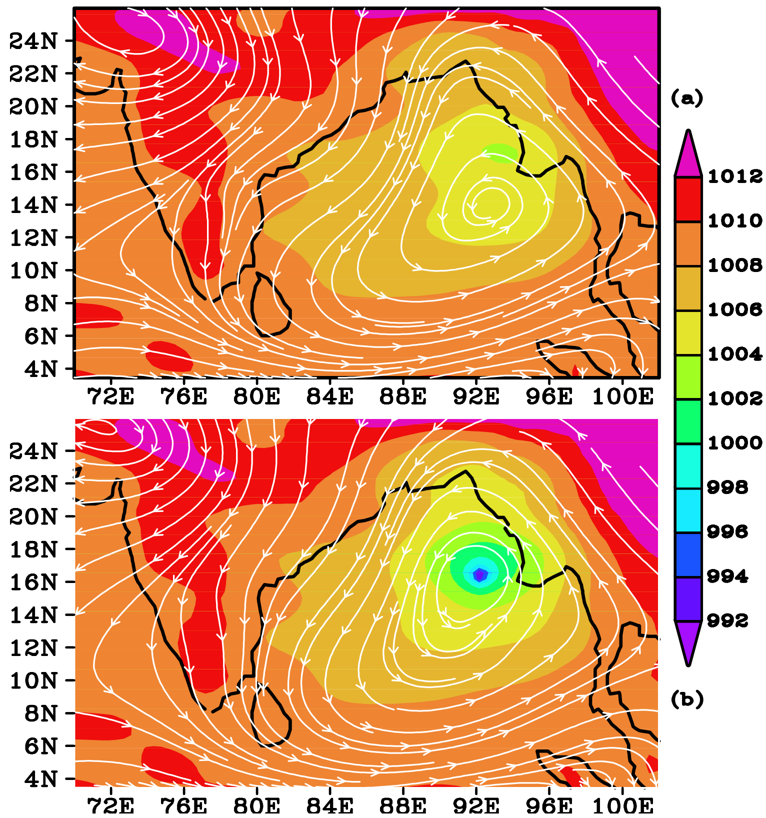

Figure 2. Distribution of initial SLP (shaded), and stream line at 850 mb, **(a)** NBOG analysis, **(b)** BOG45 analysis, valid at 00 GMT 27th October 1999.

of wind information is clearly seen in the horizontal flow.

Figure 3 shows the vertical cross-sections through the centre of the storm of wind speed, vertical velocity and potential temperature for BOG45 analysis. The wind speed (figure 3a) distribution shows lowest winds in the centre and higher winds in the eastern sector of the storm. Asymmetry in the wind distribution is clearly visible with slightly higher wind in the eastern sector compared to the western sector. Like observed vertical motions, much weaker (figure 3b) vertical motions occur in the centre with maximum vertical motion in the upper troposphere and to the west and east of the centre. The vertical motion is stronger in the western sector compared to the eastern sector. A weak potential temperature anomaly (figure 3c) is produced in the upper troposphere, a result that differs from Zhao and Braun (2001), who found a warm anomaly in the lower as well upper troposphere in their wind assimilation case. Our findings are similar to that of Xiao *et al* (2000) who also did not observe any warm anomaly in the center in lower troposphere.

Figures 4, 5 and 6 show the vertical cross section of wind speed, vertical motion, and potential temperature for BOG90 (figure 4), BOG135 (figure 5), and BOG180 (figure 6) analysis respectively, to illustrate the change caused by the increased size of vortex. From the figures 3(a), 4(a), 5(a) and 6(a) it is clear that when RMW is increased from 45 to 180 km the maximum wind speed is increased from 18 to 27 m/s. Though distribution of wind speed is the same in all cases, we observed significant changes in the vertical motion distribution by increased RMW from 45 to 180 km. In the case of BOG90 and BOG135 the vertical motion is stronger towards the east of the centre and in the upper troposphere. The maximum vertical motion cell, which was to the west of centre of storm in the case of BOG45 (figure 3) is almost absent in the case of BOG90 (figure 4) and BOG135 (figure 5). In the case of BOG180 (figure 6), unlike the observed, the vertical motion structure is completely changed with larger vertical motion present over the centre of storm. The distribution of potential temperature seems to be unchanged from BOG45 to BOG180. This shows that the structure of vertical motion is very sensitive to the vortex size. When we specify a large vortex the vertical motion structure is unrealistic. Christopher *et al* (2001) suggested putting RMW equal to two-grid lengths of the model resolution. While Zhao and Braun (2001) suggested RMW

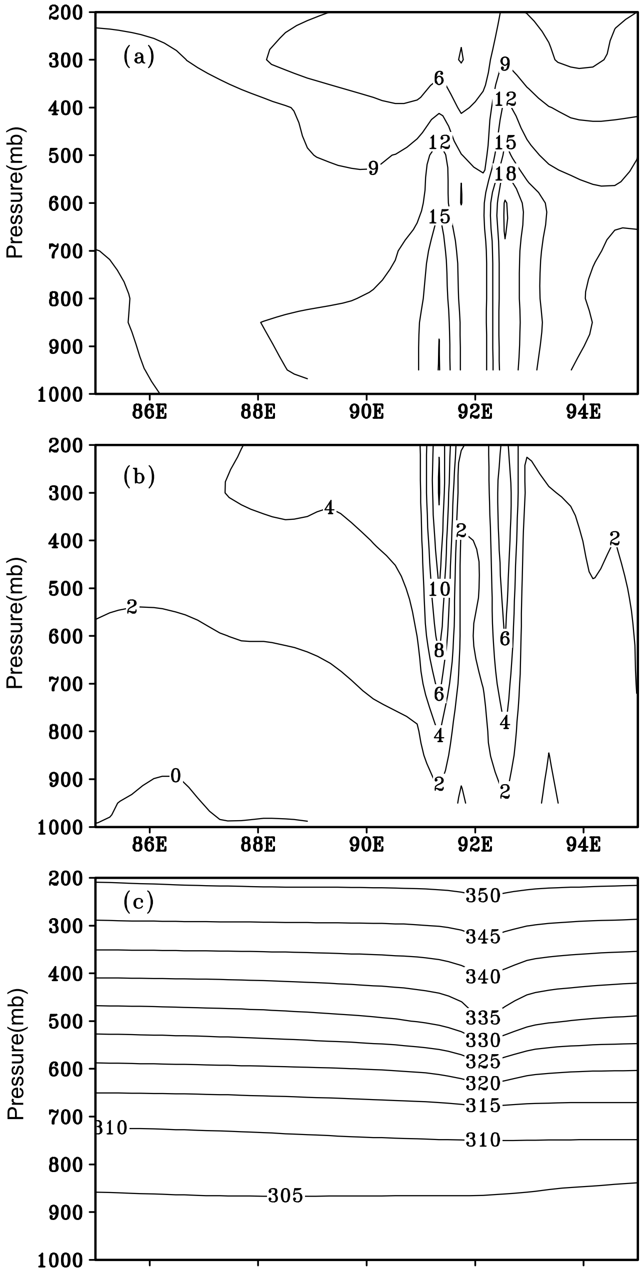

Figure 3. East–west cross sections through the centre of the vortex for BOG45 analysis valid at 00 GMT of 27th October 1999, **(a)** wind speed (m/s), **(b)** vertical motion (cm/s), and **(c)** potential temperature (K).

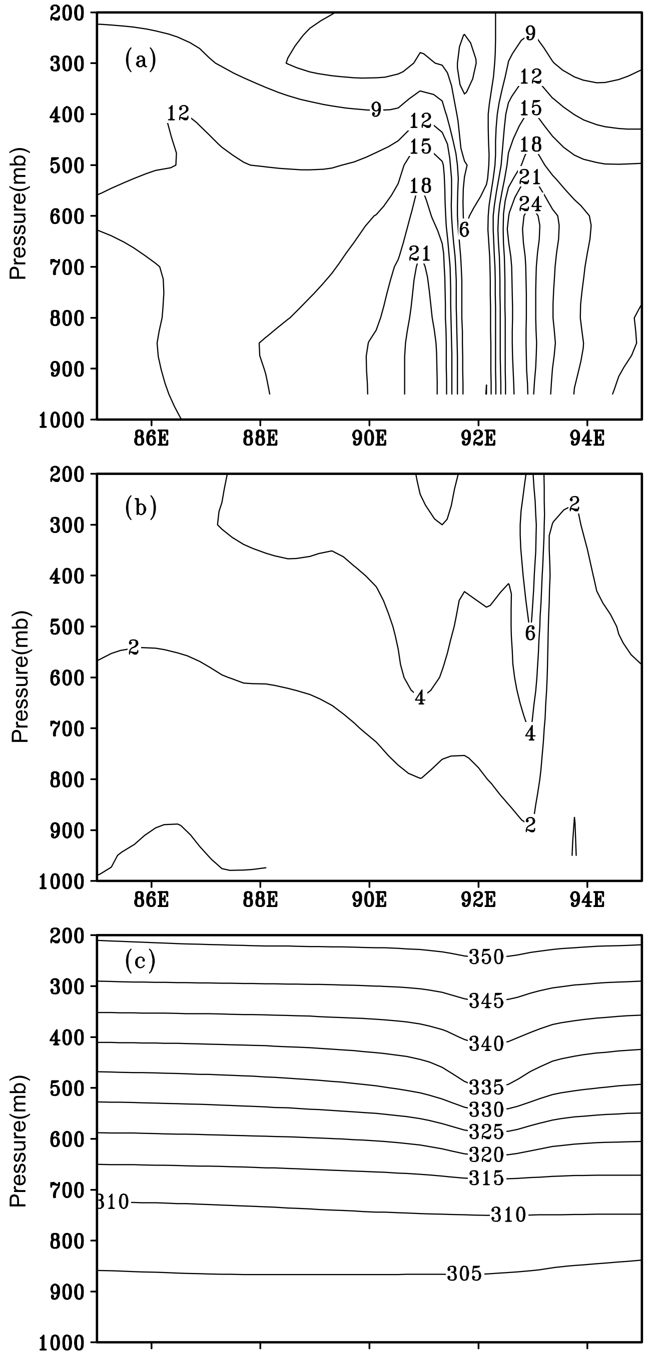

Figure 4. East–west cross sections through the centre of the vortex for BOG90 analysis valid at 00 GMT of 27th October 1999, **(a)** wind speed (m/s), **(b)** vertical motion (cm/s), and **(c)** potential temperature (K).

equal to three-grid lengths of the model resolution. In this study we got realistic vertical motion structure in BOG45, BOG90, and BOG135, but we show in the next section that track and intensity are better simulated by BOG135. Like Zhao and Braun (2001), this study also suggests that RMW should be three-grid lengths to the model resolution.

3.2.2 *Forecast impacts*

Five (one with NBOG and four with BOG analysis) 72 hour forecasts were made from 00 GMT of 27th October 1999. Figure 7 shows the simulated tracks and the observed track of the Bay of Bengal cyclone. Without the bogus vortex, the NBOG experiment shows significant errors in the initial position of the storm and a much too rapid movement in northwest to north direction, in contrast to an observed west–northwest motion. In contrast, the specified vortex BOG45 moves in the observed west–northwest direction from initial time up to

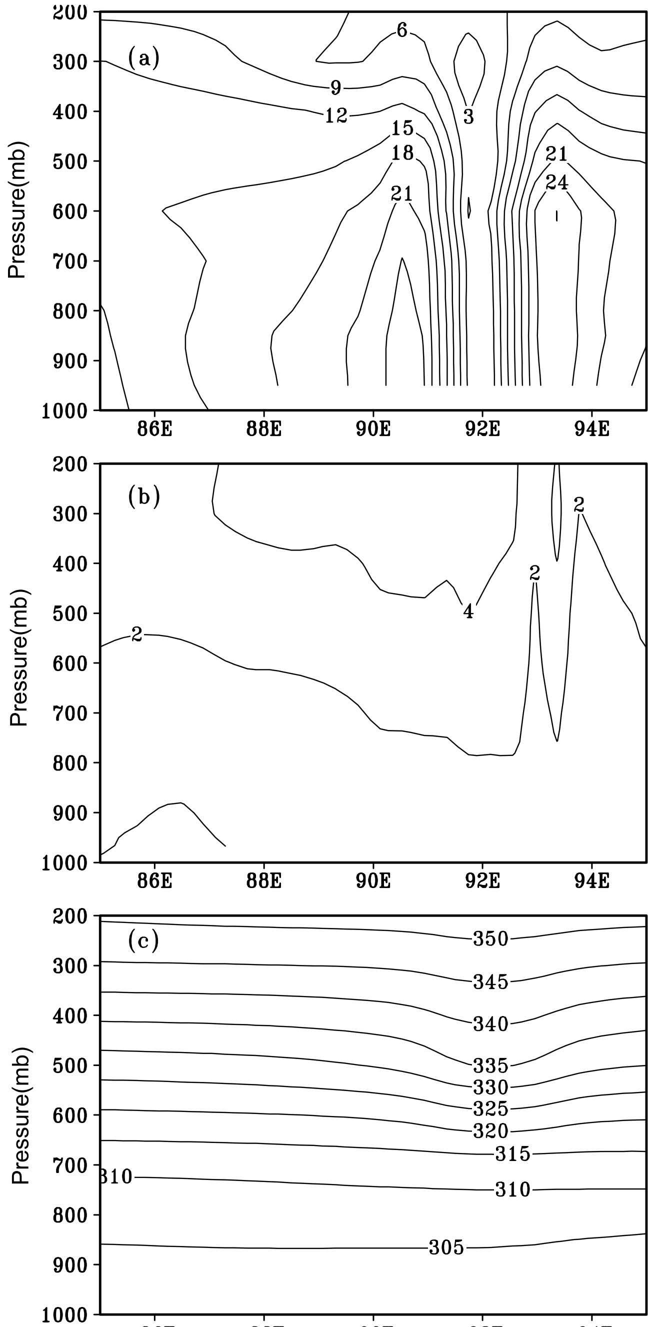

Figure 5. East–west cross sections through the centre of the vortex for BOG135 analysis valid at 00 GMT of 27th October 1999, **(a)** wind speed (m/s), **(b)** vertical motion (cm/s), and **(c)** potential temperature (K).

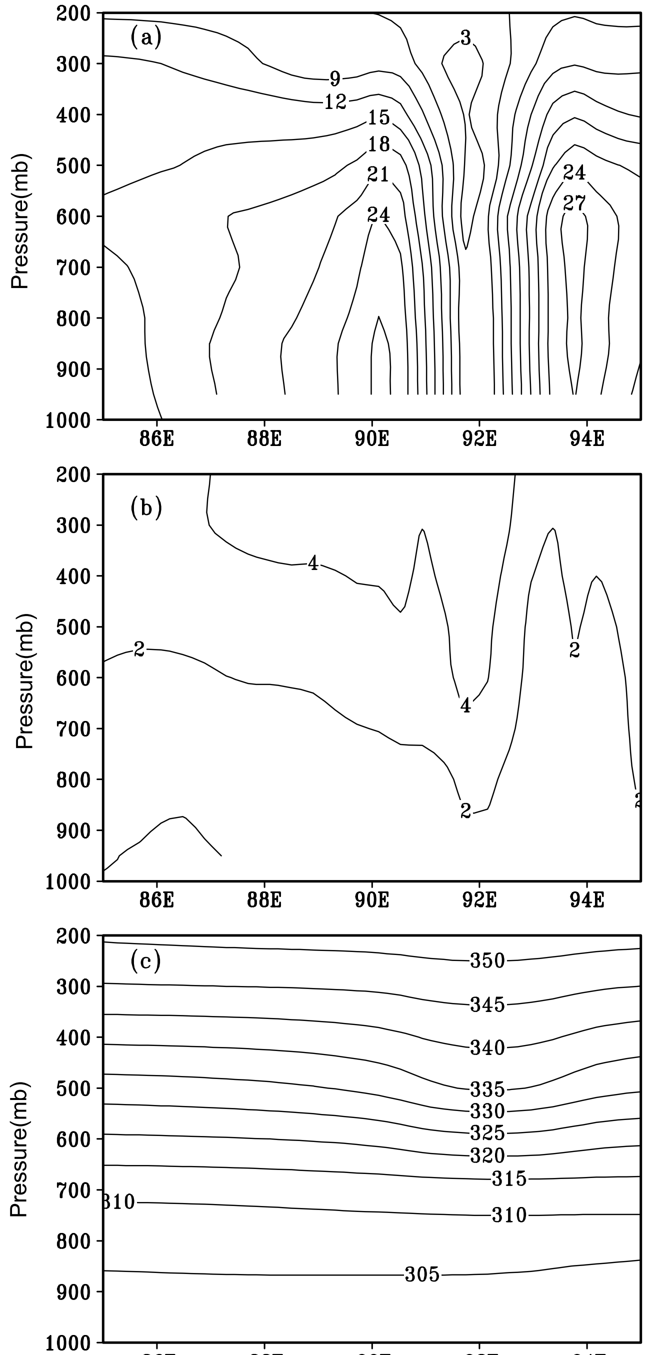

Figure 6. East–west cross sections through the centre of the vortex for BOG180 analysis valid at 00 GMT of 27th October 1999, **(a)** wind speed (m/s), **(b)** vertical motion (cm/s), and **(c)** potential temperature (K).

24 h. After 24 h the BOG45 movement becomes very slow and simulated cyclone moved to the north of the observed position. The BOG90 follows observed cyclone closely but movement is very slow after 24 h. Through the entire integration, the track forecast for BOG135 remained remarkably good, with model storm making landfall over approximately ~ 50 km away from observed but about 3 h late. The performance of BOG180 is also good but not better than BOG135. Figure 8 shows the position errors for 24, 48 and 72 h for NBOG, BOG45, BOG90, BOG135, and BOG180, respectively. Significant improvements are seen in the track forecast with BOG135 simulation.

Time series (at 6 h intervals) of maximum low level (850 mb) wind and minimum sea level pressure are shown in figure 9 and figure 10, respectively. From figure 9, it is apparent that the bogus

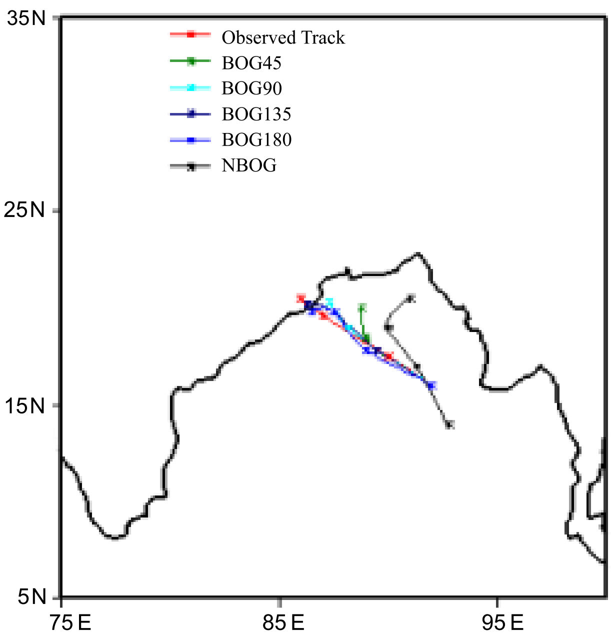

Figure 7. Model simulated tracks are compared to the observed track. The symbol (∗) indicates the daily storm position valid at 0000 GMT of each day starting from 00 GMT of 27th October to 30th October.

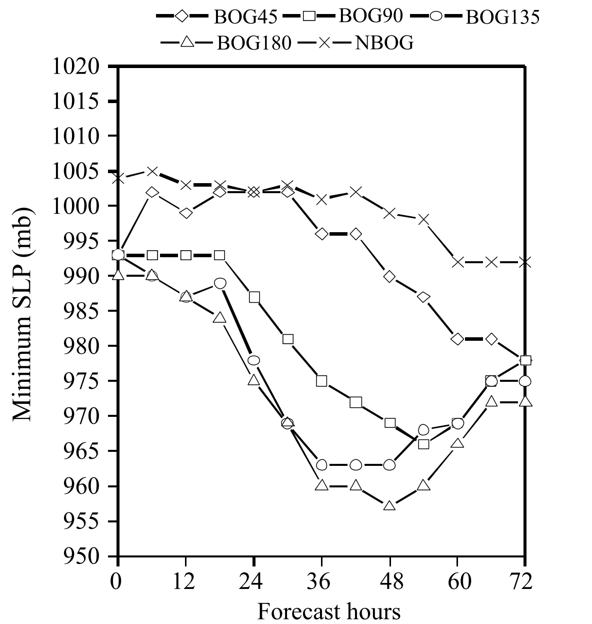

Figure 9. Time series (at 6-h intervals) of minimum sea level pressure (mb) for NBOG as well as BOG simulations.

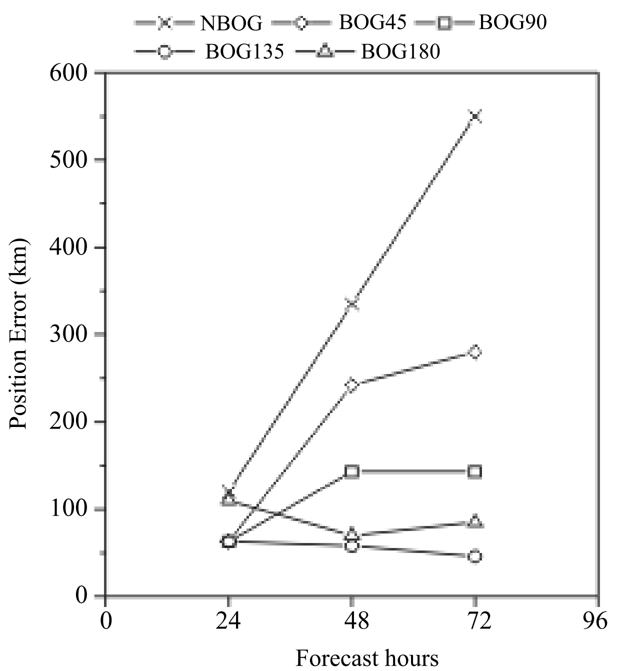

Figure 8. Position errors versus forecast time for NBOG as well as BOG simulations.

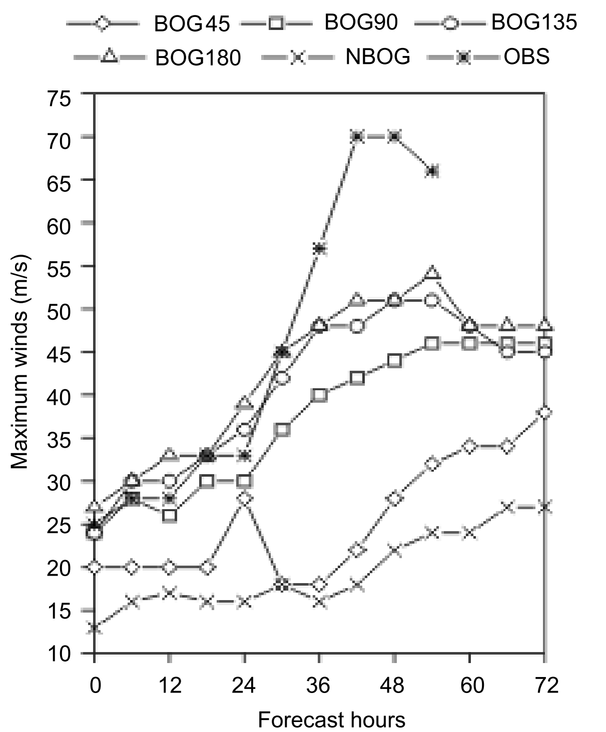

Figure 10. Time series (at 6-h intervals) of maximum wind speed (m/s) for NBOG as well as BOG simulations.

scheme, which specifies a 45 km, RMW (BOG45) leads to a rapid weakening of the storm in the first few hours. By 36 h, the storm has reached its initial intensity. The observed intensity peak reaches to 70 m/s at 18 GMT of 28th October 1999. The maximum winds in BOG45 begin at 20 m/s, weaken to 18 m/s in the first 24 h, and then increase gradually to 35 m/s by 72 h (00 GMT of 30th October 1999). Thus the course of intensification produced by BOG45 is opposite to the observed intensification. This reinforces the point that a smaller RMW is not sustainable with a grid spacing of 45 km.

Simulation of BOG90 exhibits nearly constant intensity for the first 18 h. The lack of a large adjustment in the first few hours suggests that the structure imposed is closer to that preferred by MM5. The maximum wind in BOG90 begins at 24 m/s then increases to 44 m/s at 06 GMT of 29th October 1999. This shows that the intensification in BOG90 is delayed by 18 h compared to observed intensification. Compared to NBOG simulation the significant improvement is seen in BOG90 in simulating the storm.

Simulations of BOG135 and BOG180 show similar behaviour in terms of intensification of the storm. It appears that for 45 km horizontal resolution of MM5 simulations, BOG135 and BOG180 are the suitable bogus options, as indicated by the patterns of cyclone intensification. The intensity peak of BOG135 and BOG180 occur simultaneously and matches with the observed intensity peak (18 GMT of 28th October 1999). The storm in BOG135 and BOG180 is about 40 mb deeper than in NBOG with maximum winds of about 52 m/s as opposed to 22 m/s in the case of NBOG. The deepening rate and the increase in maximum winds are in phase with one another in BOG135 and BOG180 run. From figures 9 and 10 it can be seen that BOG135 and BOG180 succeeded in correctly forecasting the intensification of the storm. It is also interesting to note that intensification (from wind comparison) ceased at approximately the same time as observed. The difference between model (BOG135 and BOG180) and observed intensity during mature stage may be attributed to the coarse resolution of the model, which was unable to resolve the very fine structure of the eyewall regions.

Based on the analysis of the structure of the initial vortex, intensity and track of the simulated cyclone it appears that RMW should be three-grid lengths of the model resolution.

4. Conclusions

The effectiveness of the tropical cyclone bogussing technique for creating bogus vortices in numerical simulations of tropical cyclone is examined using the PSU–NCAR nonhydrostatic model (MM5). The tropical cyclone bogussing scheme of Christopher *et al* (2001) is applied to the Orissa super cyclone (1999) over the Bay of Bengal. Use of the specified vortices produced a considerable improvement in the forecast up to 72 h. The use of specified vortex reduced the track and intensity forecast error significantly when compared to the integration with NBOG analysis.

With more accurately represented initial vortex structure the model successfully predicted changes in the storm intensity. Best results in terms of track and intensity prediction are obtained by vortex with RMW equal to three-grid lengths of the model, which is consistent with the finding of Zhao and Braun (2001), though some of the findings of the present study differ from Zhao and Braun (2001). For example we did not get any warm anomaly in lower troposphere in the vortex centre after wind assimilation in the specified vortex. Xiao *et al* (2000) also did not observe any warm anomaly in the vortex centre with wind assimilation in the bogus vortex. We also obtained realistic structure of vertical motion in the bogussing vortex, that is strong upward vertical motions are away from centre. But in the case of Zhao and Braun (2001) they had strong upward motion in the centre of the storm. Inclusion of more accurate structure of the vortex derived from observed satellite observations may have better impact on the forecast.

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