Impact of Microphysics Schemes in the Simulation of Cyclone Phailin using WRF model

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Abstract

A Very Severe Cyclonic Storm (VSCS) “Phailin” crossed Odisha coast near Gopalpur on 12 October, 2013 and caused significant damage to property due to both wind and surge. High surge (~2.3m) generated by the cyclone washed away some of the coastal structures (groins and break waters) constructed at the Gopalpur port besides causing coastal erosion. Wind damage was quite extensive around 50km radius of the cyclone track. In the present study, an attempt is made to simulate and test the capability of the state of art Weather Research and Forecasting meso-scale model (WRFV3) in capturing the wind intensity and track of cyclone accurately. The simulation has been carried out using two domains with a horizontal resolution of 27 km for domain1 and 9 km for domain2. Multiple simulations using initial conditions (NCEP FNL) at an interval of 6 hours, same cumulus parameterization and time integration schemes but with different microphysics schemes are carried out. The objective of the present study is to find the best microphysics for accurate simulation of intensity and track of tropical cyclone. Because, the main source of energy for tropical cyclone is the latent heat release (convective heating) in clouds, which depend on microphysical processes and the related cloud dynamical properties. The model was integrated for 108 hours starting from 9 October, 2013 to 13 October, 2013. Simulated features include track, intensity, rainfall and other synoptic conditions. As a test of the model performance, some observed features (track, maximum sustained wind, and sea level pressure) were compared with simulations and it was observed that simulations with WRF Single Moment-3 (WSM3) class microphysics scheme compare well with observations. Other synoptic features like, low level divergence, vorticity, and simulated rainfall are also discussed in relation to model performance. Impacts of Phailin on coastal structures are also discussed.

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1. Introduction

Very severe cyclonic storm (VSCS) Phailin originated over Tenasserim coast on 6 October 2013 as a remnant cyclonic circulation over the South China Sea. The cyclonic circulation then developed as a well marked low pressure centre (12.0°N, 98.5°E valid 0600 UTC) at the level of T1.0 on 7 October and as a depression (T1.5) over the same region on 8 October with center at 12.0°N and 96.0°E. Moving west-northwestwards, it further intensified into a deep depression (T2.0) centered at 12.5°N, 94.0°E at 2100UTC on the same day. The intensity became T2.5 at 1000 UTC of 9 October with centre at 13.5°N, 92.5°E. It further intensified into a severe cyclonic storm (SCS) at the level of T3.5 at 0230 UTC of 10 October (14.7°N, 91.1°E) and into a VSCS (T4.0) at 0600 UTC of 10 October (15.1°N, 90.6°E). Later the system went on rapid intensification and reached the intensity level T6.0 at 0300 UTC of 11 October 2013, because of continuous organization of eye and spiral bands. System continued to move northwestern till landfall near 19.26°N, 84.82°E (near Gopalpur, Odisha) at 1600 UTC of 12 October 2013. At the time of landfall Phailin attained maximum sustained wind (MSW) speed of 115knots (215kmph) and central pressure of 940 hPa with pressure drop of 66hPa (IMD 2013). India Meteorological Department (IMD) predicted the genesis, intensity, track, point and time of landfall and the associated storm surge and adverse weather accurately 4 to 5 days in advance. However, the forecast issued by the Joint Typhoon Warning Centre (JTWC), USA was different which indicated MSW of 140 knots and gust of 170 knots at 1130 hrs on 12 October with landfall position at 18.2°N and 85.7°E. The difference in forecast made by IMD and JTWC was more apparent after the system underwent an eyewall replacement cycle on 12 October at 1130 hrs. Thus, it is pertinent to further examine the detailed synoptic features of the cyclone with different physics and dynamical schemes using Advanced Research Weather Research and Forecasting (ARW-WRF, hereafter WRF) mesoscale model developed at National Center for Atmospheric Research (NCAR) because of its superior performance in generating fine-scale atmospheric structures as well as its better forecast skill (Otkin et al. 2005; Pattanayak and Mohanty 2008).

2. Description of the model and Model Equations

The model used in this study is the non hydrostatic WRF version 3.4.1 model, a mesoscale next generation mesoscale model (MM5) which incorporates recent and new physics parameterization schemes including some of the schemes of the MM5 model. The physics parameterization schemes used in WRF can be found in Skamarock et al. (2008). The model dynamic solver integrates the flux form of compressible non hydrostatic Euler equation as:

$$\partial_t U + (\nabla \cdot Vu) - \partial_z (p \phi_t) + \partial_\eta (p \phi_\eta) = F_U$$

$$\partial_t V + (\nabla \cdot Vv) - \partial_z (p \phi_\eta) + \partial_\eta (p \phi_t) = F_V$$

$$\partial_t W + (\nabla \cdot Vw) - g(\partial_\eta p - \mu) = F_W$$

$$\partial_\pi \Theta + (\nabla \cdot V\theta) = F_\theta$$

$$\partial_\pi \mu + (\nabla \cdot V\mu) = 0$$

along with the diagnostic relation for the inverse density

$$\partial_\pi \phi = -\alpha \mu$$

and the equation of state

$$p = p_o (R_o \theta / p_o \alpha)^\gamma$$

Where, the vertical coordinate $\eta = (p_s - p_u) / \mu$, $p_u$ is the mass per unit area, $p_s$ is the hydrostatic
component of the pressure, and \( p_s \) and \( p_w \) refer to values along the surface and top boundaries, respectively.

\[
\vec{V} = \mu v = (U, V, W), \quad \Omega = \mu \eta, \quad \Theta = \mu \theta
\]  

\( v = (u, v, w) \), the covariant velocities in the two horizontal and vertical directions, respectively, while, \( \omega = \frac{\eta}{\rho} \) is the contravariant ‘vertical’ velocity. \( \Theta \), is the potential temperature. Also appearing in the governing equations of the WRF model are the non-conserved variables \( \Theta = g \zeta \) (the geopotential), \( \rho \) (pressure), and \( \alpha = 1/\rho \) (the inverse density).

In Eqs. 1-7, the subscripts \( x, y \) and \( \eta \) denote differentiation,

\[
\nabla \cdot \vec{V} a = \partial_x (Va) + \partial_y (Va) + \partial_\eta (\Omega a) , \quad \text{and} \quad \nabla \cdot \vec{V} a = U \partial_x a + V \partial_y a + \Omega \partial_\eta a .
\]

Here ‘\( a \) ’ represents a generic variable. \( \gamma = c_p / c_v = 1.4 \), the ratio of the heat capacities for dry air, \( R_s \) is the gas constant for dry air, and \( p_o \) is a reference pressure (typically \( 10^5 \) Pascals). The right-hand-side (RHS) terms \( F_v , F_v , F_w \) and \( F_o \) represent forcing terms arising from model physics, turbulent mixing, spherical projections, and the earth’s rotation.

The variables in these equations are in conservative forms following Ooyama (1990). Following Laprise (1992) the equations are formulated using a terrain following mass vertical coordinate. In order to maintain the numerical stability the third order Runge-Kutta (RK3) scheme has been used for the time-split integration, while the high frequency acoustic waves are integrated over smaller time steps. The schemes used to study the impact of microphysics parameterization are listed in Table 1.

**Table 1. Microphysics parameterization schemes.**

<table>
<thead>
<tr>
<th>Name of the scheme</th>
<th>Acronyms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kessler scheme</td>
<td>KES</td>
</tr>
<tr>
<td>Lin et al. scheme</td>
<td>LIN</td>
</tr>
<tr>
<td>WRF single moment 3-class simple ice scheme</td>
<td>WSM3</td>
</tr>
<tr>
<td>WRF single moment 5-class scheme</td>
<td>WSM5</td>
</tr>
<tr>
<td>Ferrier (new Eta) microphysics</td>
<td>FER</td>
</tr>
<tr>
<td>WRF single moment 6-class scheme</td>
<td>WSM6</td>
</tr>
<tr>
<td>Thompson graupel scheme</td>
<td>TG</td>
</tr>
<tr>
<td>Milbrandt-Yau 2-moment scheme</td>
<td>MY2</td>
</tr>
<tr>
<td>Morrison 2-moment scheme</td>
<td>M2</td>
</tr>
<tr>
<td>WRF double moment 5-class scheme</td>
<td>WDM5</td>
</tr>
<tr>
<td>WRF double moment 6-class scheme</td>
<td>WDM6</td>
</tr>
<tr>
<td>NSSL 2-moment with CCN prediction</td>
<td>N2CCN</td>
</tr>
</tbody>
</table>

3. Model Domain and Dynamic Options

Numerical experiments are conducted with two domains; domain1 (coarse) and domain2 (finer). The domains are run simultaneously by one-way nested run option. The horizontal grid resolution of domain1 is 27km and it covers the BoB. As Phailin moved from its point of genesis at South China Sea and had landfall over south Odisha coast, a high resolution (9km) domain2 was chosen to cover the entire region. The details of the domains and dynamic options used in the WRF model are listed in Table 2.

4. Model Initial and Boundary Conditions

The United States Geological Survey (USGS) 10m (2m) resolution terrain topographical data have been used for domain1(domain2) in the WRF preprocessing system (WPS). Initial and boundary conditions are obtained from the http://rda.ucar.edu/datasets/ds083.2/. These NCEP FNL (Final) Operational Global Analysis data are on 1-degree by 1-degree grids prepared operationally every six hours. Simulations were initiated on 9 October 2013 0600 UTC with lateral boundary condition and were carried upto 13 October 2013 1800 UTC. The model was run upto 108hr, and
the model output generated every three hours were taken into consideration for comparison with features such as track position, mean sea level pressure (SLP), MSW observed by IMD (IMD 2013) and the model simulated 24-hour accumulated precipitation was also compared with Tropical Rainfall Measuring Mission (TRMM). The other synoptic features such as divergence and vorticity simulated by the model were also discussed.

Table 2. Details of model dynamics and domain of study.

<table>
<thead>
<tr>
<th>Dynamics</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Equation</td>
<td>Non hydrostatic</td>
</tr>
<tr>
<td>Time Integration</td>
<td>3rd order Runge-Kutta Scheme</td>
</tr>
<tr>
<td>Horizontal grid type</td>
<td>Arakawa-C grid</td>
</tr>
<tr>
<td>Domain</td>
<td></td>
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<tr>
<td>Map projection</td>
<td>Mercator</td>
</tr>
<tr>
<td>Domain center</td>
<td>93ºE, 13ºN</td>
</tr>
<tr>
<td>Number of domains</td>
<td>2 (one coarse domain1 and one finer domain2)</td>
</tr>
<tr>
<td>Vertical levels</td>
<td>51 sigma levels</td>
</tr>
<tr>
<td>Horizontal grid distance</td>
<td>27km(domain1), 9km(domain2)</td>
</tr>
<tr>
<td>Time step</td>
<td>90s(domain1), 30s(domain2)</td>
</tr>
<tr>
<td>Number of grid points</td>
<td>111(WE), 104(SN) in domain1</td>
</tr>
<tr>
<td></td>
<td>184(WE), 163(SN) in domain2</td>
</tr>
</tbody>
</table>

5. Experimental procedure and scheme selection

Sensitivity studies for the Phailin were carried out in order to determine the best microphysics parameterization scheme for track and intensity prediction. Results from finer resolution (domain2, 9km) have been used for the analysis. In all the experiments, the Kain-Fritsch (KF) cumulus parameterization scheme, Yonsei-University (YSU) planetary boundary layer (PBL) scheme were kept fixed (Osuri et al. 2012). The model output and the IMD observed track were compared concurrently. The track error (Ei in degrees) is computed by using the formulation:

\[ E_i = \sqrt{(lat_{wrf} - lat_{imd})^2 + (lon_{wrf} - lon_{imd})^2} \]

and the root mean square error (RMSE) is computed by using:

\[ \text{RMSE} = \sqrt{\frac{\sum E_i^2}{n}} \]

Where, \( E_i \) represents the error at \( i^{th} \) position of the storm, \( n \) is the number of positions/observations at a particular time. The best scheme has been chosen on the basis of both the propagation of simulated track and the RMSE. Analysis of intensity in terms of 10-m MSW and central SLP (CSLP) has also been conducted in a similar fashion. These are then compared with the IMD data (IMD 2013) and RMSE is then computed. The best scheme is chosen on the basis that gives the least RMSE.

6. Results and Discussion

6.1 Impact of Phailin on coastal structure

Impact of Phailin on coastal structure was studied by conducting field surveys with help of DGPS ArcPad to estimate the damage caused to the breakwaters and groin fields of Gopalpur port by the Phailin. It is observed that elevation height and length of northern breakwater reduced by 0.99 m and 126.3 m respectively while for southern breakwater it is 2.3 m and 656 m respectively. Similarly the impact on groin fields was quite significant. The elevation height reduced from between 0.38 to 5.11 m while the length reduced from between 0.3 to 88 m for the 11 groins of the north of the port.
6.2 Track

The microphysics parameterization schemes explicitly handle water vapour, cloud and precipitation processes and also the microphysical processes of melting of snow, graupel and cloud ice hydrometers, suppression of falling rain by evaporation. In this study, 12 different microphysics parameterization schemes available in WRFV3.4.1 model have been considered along with KF cumulus parameterization, and YSU PBL scheme. The propagation of tracks is shown in Fig. 1. Figure 2 depicts the RMSE of track with IMD observations. The 24-, 48-, 72-, and 96-hour forecast track errors are shown in Fig. 3.

The RMSE of tracks (Fig. 2) indicates that the WSM3 scheme produces a relatively smaller track error as compared to other schemes. The maximum track error is 155.4 km for the KES scheme. There is no significant variation in RMSE between LIN, WSM5, FER, WSM6, TG, WDM5, WDM6 schemes. The 24-hour forecast least track error is 46 km for WSM5, whereas maximum track error is 70 km for KES and WDM5 schemes (Fig. 3). There is no significant difference in 24-hour forecast track error in LIN, WSM3, FER, WSM6, MY2, M2 schemes. Similarly, 48-hour forecast least track error is 38 km for LIN followed by 56 km for WSM6 and 57 km for WSM3 and WSM5 schemes (Fig. 3). The 72-hour forecast least track error is 48 km for LIN followed by 84 km for WSM3 and 93 km for WDM6 (Fig. 3). The 96-hour forecast least track error is 31 km for the TG scheme followed by 56 km for WSM5, 64 km for WDM5 and 65 km for WSM3 scheme. The RMSE of track for 24-, 48-, 72-, and 96-hour forecast is the least (67 km) for the WSM3 scheme. The 108-hour forecast RMSE of track (Fig. 2) is the least for the WSM3 scheme (82 km) followed by LIN (90 km) and the simulated track is closest to the observation (Fig. 1). Only the WSM3 scheme simulates the landfall point which is very close to the observation between 1500 UTC to 1800 UTC of 12 October. The results suggest that for early warning (108-hr) of cyclones the track simulations by WSM3 are very close to the observed track and hence may be preferred over other schemes.

![Fig. 1. Simulated tracks of Phailin by different microphysics parameterization schemes.](image)

6.3 Central sea level pressure

Figure 4 depicts the CSLP. All the schemes predict the same CSLP at 0600 UTC of 9 October and continue upto 1200 UTC of 9 October (Fig. 4). Also the initial position of the storm is well simulated by all the schemes. The CSLP at 0600 UTC and 0900 UTC of 9 October is simulated as 996 hPa and dropped to 992 hPa on 1200 UTC of 9 October when the intensity of the storm was at CS level. Further the CSLP is dropped when the storm attains the intensity of VSCS at 0600 UTC of 10 October. At this time the CSLP varies from 960 hPa to 970 hPa for all the schemes. On 0000 UTC of 11 October only the WSM3 scheme simulates the CSLP of 945 hPa which is very close to the observation (Fig. 4). Only the WSM3 scheme predicts the CSLP of 940 hPa from 1200 UTC of 11 October to 1500 UTC of 12 October which is same as the observed value (Fig. 4) while other schemes overestimate the CSLP of Phailin.
Fig. 2. RMSE of track compared with IMD observations (in degree).

Fig. 3. Track error (at 24, 48, 72 and 96 hours).

Fig. 4. Time variation of model simulated CSLP with IMD observations (hPa).

6.4 Maximum Sustained Wind

Figure 5 depicts the 10-m MSW speed along with IMD observation. At 0900 UTC of 9 October WSM3 scheme simulates the MSW speed of 46 knots while other schemes simulate MSW speed of 50 knots. When the storm attains the VSCS intensity level the MSW speed of 68 knots is well simulated by WSM3 scheme and matches well with the observation whereas other schemes overestimate the MSW speed.
6.5 Precipitation

Figure 6 shows the 24-hour accumulated rainfall by different schemes along with TRMM observation. Precipitation is an important parameter to be simulated accurately by any model. Before the landfall (on 11 and 12 October) precipitation is confined mainly over the ocean and could not be validated with observation. Figure 6 shows the 24-hr accumulated precipitation valid 0300 UTC of 13 October along with TRMM observation. A close inspection in these figures shows that the precipitation simulated by WSM3 scheme varies from 10 to 30 cm along Odisha and coastal Andhra Pradesh while TRMM observation varies from 2 to 16 cm in coastal Andhra Pradesh and 6 to 14 cm in Odisha. Other microphysics schemes overestimate the precipitation as compared to TRMM.
6.6 Low level wind convergence and Vorticity

Mathematically, the two dimensional expression for the divergence (D) of a fluid element at a constant pressure is $D = \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right)$. For positive values of $\frac{\partial u}{\partial x}$ and $\frac{\partial v}{\partial y}$ the fluid element expands while for negative values it is compressed. The expression for the vertical component ($\zeta$) of the vorticity at a constant pressure is $\zeta = \left( \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right)$. The divergence is always one order of magnitude less than the planetary vorticity ($f$). This is necessary to make the vorticity equation $D t + \eta \frac{\partial \eta}{\partial t} = -D$, energetically consistent as the absolute vorticity $\eta = f + \zeta$. From this equation it is clearly understood that the pattern of convergence and divergence are strongly coupled with changes in the absolute vorticity. Hence, an area with low level convergence with vorticity maxima is associated with convection that favours the development of a cyclone which is well captured by all the schemes under consideration (figure not shown).

7. Conclusion

The 108-hour forecast RMSE of track is the least for the WSM3 scheme. Only the WSM3 scheme predicts the CSLP of 940 hPa from 1200 UTC of 11 October to 1500 UTC of 12 October which is same as the observation and also simulates the landfall point which is very close to the observation. The intensity in terms of MSW speed simulated by WSM3 scheme matches well with the observation while other microphysics schemes overestimate the MSW speed. Rainfall, an important parameter, is well captured by WSM3 scheme as compared to TRMM while other schemes overestimate the intensity of rainfall and the spatial distribution is far from the observed rainfall. However, the suitability of WSM3 scheme for operational forecast of cyclone may be examined by conducting more case studies. The damage caused to the coastal structures, life and property can be minimized by accurate prediction of cyclonic storms adopting best performing schemes/models.

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References