Sensitivity of simulated cyclone Gonu intensity and track to variety of parameterizations: Advanced hurricane WRF model application

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Domain configuration and several physical parameterization settings such as planetary boundary layer, cumulus convection, and ocean–atmosphere surface flux parameterizations can play significant roles in numerical prediction of tropical cyclones. The present study focuses to improve the prediction of the TC Gonu by investigating the sensitivity of simulations to mentioned configurations with the Advanced Hurricane WRF model. The experiments for domain design sensitivity with 27 km resolution has been shown moving the domains towards the east improve the results, due to better account for the large-scale process. The fixed and movable nests on a 9-km grid were considered separately within the coarse domain and their results showed that despite salient improvement in simulated intensity, an accuracy reduction in simulated track was observed. Increasing horizontal resolution to 3 km incredibly reduced the simulated intensity accuracy when compared to 27 km resolution. Thereafter, different initial conditions were experimented and the results have shown that the cyclone of 1000 hPa sea level pressure is the best simulation initial condition in predicting the track and intensity for cyclone Gonu. The sensitivity of simulations to ocean–atmosphere surface-flux parameterizations on a 9-km grid showed the combination of ‘Donelan scheme’ for momentum exchanges along with ‘Large and Pond scheme’ for heat and moisture exchanges provide the best prediction for cyclone Gonu intensity. The combination of YSU and MYJ PBL scheme with KF convection for prediction of track and the combination of YSU PBL scheme with KF convection for prediction of intensity are found to have better performance than the other combinations. These 22 sensitivity experiments also implicitly lead us to the conclusion that each particular forecast aspect of TC (e.g., track, intensity, etc.) will require its own special design.

Keywords. Tropical cyclone; Gonu; surface fluxes; PBL; cumulus convection; AHW.

1. Introduction

Tropical cyclones (TCs), due to their nature, are recognized as the most common and devastating of all natural disasters. The improvement of TCs track and intensity prediction can

significantly help in reducing loss of life and property. The previous studies show that the numerical forecast using dynamical models can provide better TCs track and intensity prediction as compared to synoptic and statistical methods (Mohanty and Gupta 1997; Rao and Bhaskar Rao

2003; Mandal *et al.* 2004; Osuri *et al.* 2012). Nearly 80–90% of TCs attain intensity of 33 m/s (Frank and George 2007). Among all TCs, about 7% occur in the north Indian Ocean (NIO), including the Arabian Sea (AS) and the Bay of Bengal (BoB), and about 2% of all TCs have their origin in AS (World Meteorological Organization (WMO) technical report 2014). Even though the period of occurrence of TCs in AS is lower than any other region of the world, the inadequate prediction of TCs over this region had caused extensive devastation (e.g., cyclone Gonu). When we review the recent studies on the simulation of the TCs over NIO, it is clear that simulation of Gonu is more problematic compared with other TCs. The results of Osuri *et al.* (2012) using WRF(ARW) show the best of peak intensity predicted for Gonu (one of five selective cases) was 35 m/s that there is salient difference about 30 m/s than India Meteorological Department (IMD) reference data as well as the trend of evolution of intensity is not captured and while the track predicted was rather satisfactory, but the model could not predict the first landfall over Oman. Osuri *et al.* (2013) presented the satisfactory performance of the WRF(ARW) model based on the 100 forecasts for 17 TCs over NIO; however, the prediction of Gonu (one of 17 selective cases) was a problem where the model predicted the first landfall over Oman with some southward displacement while the model could not predict the second landfall of Gonu over Iran. The best of peak intensity predicted for Gonu was 48 m/s which has a difference of about 17 m/s than IMD reference data. The results of Mohandas and Ashrit (2013) show the simulation of Gonu (one of three selective cases) using WRF(NMM) for the intensity, was underpredicted as well as the track was not satisfactory. We can add the studies of Deshpande *et al.* (2010) using MM5, Pattanayak and Mohanty (2008) used WRF and MM5 to above-mentioned configurations. In this study, we intend to improve the prediction of the TC Gonu using the Advanced Hurricane WRF(AHW) model. Kumar *et al.* (2011) used AHW model over NIO for the first time, to simulate the cyclone Sidr (2007, Bay of Bengal) which improved previous results of the cyclone. They presented the selective domains which had major impact on the simulations of TCs. The results of Kumar *et al.* (2011) also suggested that the cyclone track is controlled by large-scale features such as synoptic winds while intensity strongly depends on both local and

large-scale conditions. Kanase and Salvekar (2011) investigated the sensitivity of the TC Laila simulations to initial conditions. Their results show the simulations dependent on the initial condition and simulated results are improved when the initial conditions are applied prior to the formation of low. The results of Kumar *et al.* (2011) prove the findings of Kanase and Salvekar (2011). Among all of the physical parameterizations, PBL and convection have long been recognized as processes of central importance in the genesis and intensification of TCs (Osuri *et al.* 2012). The PBL is a critical factor (Braun and Tao 2000) because of generation of the large fluxes of heat, moisture, and momentum in this thin layer (Osuri *et al.* 2012). Davis *et al.* (2010) presented that intensity (maximum wind) and rapid intensification, as well as wind radii, were all predicted more accurately with increased horizontal resolution.

In addition, the designation of surface-flux parameterizations, including momentum due to surface waves, especially in high wind conditions and enthalpy (heat and moisture) between ocean and atmosphere are significant in the accuracy of results. It plays an important role in the prediction of TCs intensity over the ocean surface and finally, the cooling effect of the ocean mixed layer could be a key issue in the prediction of cyclone intensity (Davis *et al.* 2008).

One of the new contributions of this study is the implementation of sensitivity analysis for selective domains. By taking the route of TCs over the AS to west–northwest–southwestwards, and impact of the large-scale process (especially easterly winds) in TCs track, optimum domain design is of particular importance at the prediction of TCs intensity and track in this area. One key question, what is the appropriate time to start the simulation according to the TC life cycle? We carried out a sensitivity analysis with an initial condition to answer this question for the AS region. The proper functioning of physical parameterizations consist of cumulus convection, surface fluxes of heat, moisture, momentum, and vertical mixing in PBL will lead us to better predict TCs intensity and track in this region.

The sensitivity of the TC Gonu simulations to domain configuration (coverage, resolution and nesting), initial condition, ocean–atmosphere surface flux parameterizations (momentum, heat and moisture), planetary boundary layer (PBL) and cumulus convection physical parameterizations

Figure 1. The information of reference track for cyclone Gonu received from IMD. (a) CSLP and maximum 10-m wind and (b) IMD reference track.

were investigated with the AHW model to improve the prediction of the TC Gonu.

2. Data

Supercyclone Gonu, equivalent to Category 5 on the Saffir–Simpson scale, was one of the strongest tropical cyclones ever recorded which was formed in the Arabian Sea during the period of 1–7 June, 2007. At the peak intensity, Gonu caused 3-min sustained wind of about 240 km/hr and minimum pressure of about 920 hPa. Around 4.2 billion USD of financial losses and 78 human casualties were caused by cyclone Gonu (India Meteorological Department Report 2008).

Herein, we do not plan to explore the synoptic conditions of the cyclone Gonu formation. The performance of AHW model is evaluated in explicit simulations of supercyclone, Gonu.

The AHW is a relatively new derivative of the WRF(ARW) model that was initially developed from the community release of the WRF model after 2005 (Davis *et al.* 2008). Vortex following inner domain, 2-way nested grid system, implementation of some complementary surface fluxes parameterizations and utilities such as TC Bogus scheme (vortex replacement strategy in the initialization fields), made AHW ideal for the prediction of the multiple length scales present in hurricanes ranging from synoptic scale (1000 km or more) to the sharp gradients inside the eye wall (5–10 km). In AHW model, 1D Ocean mixed-layer model based on Pollard *et al.* (1973) was added to WRF to provide a feedback of mixing-induced sea-surface cooling to the atmosphere and forecasts were extended to 5 days.

The AHW is distinct from the Hurricane WRF (HWRF) developed by National Centers for Environmental Prediction (NCEP). HWRF is based on the NMM (non-hydrostatic mesoscale model) dynamic core of the WRF with ocean model coupling (Princeton Ocean Model) and physical GFDL surface parameterization. The HWRF does not provide operational real time forecast over NIO; however, it gives real-time experimental forecasts for NIO regions (see Gopalakrishnan *et al.* 2010; Tallapragada *et al.* 2014).

The diversity of surface parameterization accompanied with air–sea coupling (1D ocean mixed-layer model) is introduced in AHW. Convenience in model initialization and also its good performance in recent studies (e.g., Torn 2016; Davis *et al.* 2008) have motivated authors to conduct the variety of the sensitivities explained in section 3 with AHW model.

The data from NCEP global final analysis (FNL) on a $1.0^\circ \times 1.0^\circ$ grid was used to provide initial and boundary conditions for numerical simulations. Sea surface temperatures were derived from the high-resolution real-time global sea surface temperature (RTG_SST) at 1/12-degree resolution analyses dataset from NCEP Marine Modeling and Analysis Branch (MMAB). The information of cyclone Gonu reference track with 3 h resolution during 18 UTC 1 June–03 UTC 7 June 2007 has been received from IMD (figure 1). The tropical storm Gonu was developed as a depression over the east-central Arabian Sea with centre near 15.0°N , 68.0°E at 18 UTC 1 June 2007. It moved northwestward and intensified into a severe cyclonic storm with central pressure of 988 hPa, centred at 15.5°N , 66.5°E . The system moved west-northwestwards and further intensified as a supercyclonic storm and laid

Figure 2. Selective domains for sensitivity experiments with model domain coverage, nesting and horizontal resolution.

its centre at 20.0°N , 64.0°E , with minimum central pressure of 920 hPa and maximum surface wind of 127 knots. Then the storm moved further in the northwestward direction and weakened and laid its centre over northwest Arabian Sea at 20.5°N , 63.5°E , with minimum central pressure of 935 hPa. Then it gradually weakened, moved northwestward and crossed northeast Oman coast near Muscat in 22.5°N , 59.0°E with minimum central pressure of 970 hPa during 02–03 UTC of 6 June and crossed the Makran (Iran) coast near 25.0°N , 58.0°E with minimum central pressure of 988 hPa during 03–04 UTC 7 June 2007 as a cyclonic storm.

The coupled mixed layer ocean model with WRF model requires specification of an initial mixed layer depth h_0 and a deep-layer lapse rate Γ . The ocean model was initialized with h_0 and Γ equal to 50 m and 0.14 k/m, respectively in order to consider negative feedback of wind-driven ocean mixing on cyclone intensity (Davis *et al.* 2008).

3. Methodology

We considered separately three individual domains in horizontal resolution of 27 km. 145×110 grid points were taken in the x and y axes for domains

D1, D2 and D3, while the centers of these three domains are located in latitude $10^{\circ}00'$, but at different longitudes of $57^{\circ}00'$, $70^{\circ}00'$ and $83^{\circ}30'$, respectively (figure 2). It is noteworthy that after several tests in horizontal resolution of 27 km and based on the importance of location of domains (Kumar *et al.* 2011) in the simulations of TCs, we changed the first three domains towards the east until taking large-scale processes that lead the Gonu track (tables 1, 2 and figure 2) introduce the coordinates, features and configurations of the selective domains and simulations. For the third domain, we also considered fixed nest (109×109 grid points) and movable nest (109×109 grid points) at the resolution of 9 km to test the sensitivity of the simulations to horizontal resolution and nesting. Again, the horizontal resolution was improved to 3 km for achieving another movable nest (247×247 grid points) as second inner domain within D3 (figure 2). The fourth, fifth, sixth and seventh simulations were performed on these nests. The first seven simulations were initialized at 00 UTC 2 June for 6 days. The eighth and ninth simulations were performed on the D3 domain to test the sensitivity of the simulations at initial condition. The ninth simulation was initialized at 00 UTC 3 June 2007 and the tenth

Table 1. Overview of the default AHW model configuration.

Model	AHW
Time integration scheme	3rd order Runge–Kutta scheme
Spatial differencing scheme	6th order center differencing
Micro physics	WSM 6 (Hong <i>et al.</i> 2004)
Long wave radiation scheme	RRTM (Mlawer <i>et al.</i> 1997)
Short wave radiation scheme	Dudhia (1989)
Surface layer parameterization	Thermal diffusion scheme
Planetary boundary layer physics	YSU (Noh <i>et al.</i> 2003)
Cumulus scheme	Kain–Fritsch (Kain 2004)
Boundary-initial conditions	NCEP FNL (Global analysis)
Surface drag exchange parameterization	Donelan <i>et al.</i> (2004)
Surface enthalpy exchange parameterization	Large and Pond (1981)
Ocean mixed layer depth	40 m
Ocean mixed layer lapse rate	0.14 K/m
Vertical resolution	37 levels
Model top	2000 Pa

Table 2. Differences of AHW model configuration for all defined experiments.

Names of experiments	Horizontal resolution	Domain coverage	Center-point
27 km-D1	27 km	D1, 11,442,384 km ²	10°00'N, 5700E
27 km-D2	27 km	D2, 11,627,550 km ²	10°00'N, 7000E
27 km-D3	27 km	D3, 11,627,550 km ²	10°00'N, 8330E
	Horizontal resolution	Domain coverage	Nesting
9 km-fixed nesting	9 km	944,784 km ²	Fixed nesting within D3
9 km-movable nesting	9 km	944,784 km ²	Fixed nesting within D3
3 km-movable nesting-cu 0	3 km	544,644 km ²	Fixed nesting within D3
3 km-movable nesting-cu 1	3 km	544,644 km ²	Fixed nesting within D3
	Horizontal resolution	Initial condition	Duration
27 km-2 June-6 days	27 km	02 June 2007: 00 UTC	6 days
27 km-3 June-5 days	27 km	03 June 2007: 00 UTC	5 days
27 km-4 June-4 days	27 km	04 June 2007: 00 UTC	4 days
	Horizontal resolution	C_d parameterization	C_k parameterization
27 km-Charnock–Carlson and Boland	27 km	Charnock	Carlson and Boland
27 km-Donelan–Large and Pond	27 km	Donelan	Large and Pond
27 km-Donelan–Garratt	27 km	Donelan	Garratt
9 km-Charnock–Carlson and Boland	9 km	Charnock	Carlson and Boland
9 km-Donelan–Large and Pond	9 km	Donelan	Large and Pond
9 km-Donelan–Garratt	9 km	Donelan	Garratt
	Horizontal resolution	PBL scheme	Convection scheme
9 km-YSU-BMJ	9 km	YSU	BMJ
9 km-YSU-KF	9 km	YSU	KF
9 km-YSU-no	9 km	YSU	No cumulus
9 km-MYJ-BMJ	9 km	MYJ	BMJ
9 km-MYJ-KF	9 km	MYJ	KF
9 km-MYJ-no	9 km	MYJ	No cumulus

simulation was initialized at 00 UTC 4 June 2007. The first nine simulations were performed using physical parameterization schemes as the default configuration which were defined by Kumar *et al.* (2011) for his simulations (table 1). Cumulus convection, surface fluxes of heat, moisture, momentum and vertical mixing in the PBL play important roles in the development of tropical cyclones (Anthes 1982). The surface-flux parameterizations include both momentum and enthalpy (heat and moisture) exchanges. Two main parameterization schemes for momentum exchange were presented by Charnock (1955) and Donelan *et al.* (2004), and out of these two, Charnock formulation is a default scheme in mesoscale meteorological models (Krishnamurti 2005). In the Charnock relation, 10-m drag coefficient (C_d) generally increases from about 0.001–0.003 at normal TC wind strengths and it can increase to 0.005 for category 5 storms (wind $>70 \text{ m s}^{-1}$). However, in recent field observations (e.g., Black *et al.* 2007) and laboratory experiments of Donelan *et al.* (2004), reported a general consensus that C_d reaches a maximum near 0.003 at hurricane wind speeds (30–40 m s^{-1}), then stops with increasing wind speed. In the Donelan relation, C_d is lower than those from the Charnock relation for low winds with a linear increase up to a maximum near 0.0024 at high wind speeds. The ratio of the exchange coefficient of enthalpy (C_k) to C_d is introduced as an important factor in TC intensity (Emanuel 1995; Braun and Tao 2000; Davis *et al.* 2008). Three main parameterizations schemes for enthalpy (heat and moisture) exchange were presented by Carlson and Boland (1978), Large and Pond (1981) and Garratt (1992). The ratio of C_k to C_d is introduced as an important factor in TC intensity (Emanuel 1995; Braun and Tao 2000; Davis *et al.* 2008). The C_k will increase slowly in Carlson and Boland relation; stay steady in Large and Pond relation and decrease in Garratt relation with increasing wind speed. For this sensitivity experiments, six simulations were performed with the various configurations for surface flux parameterizations on two horizontal grid resolutions (27 km on the third domain and 9 km on movable nest). The names and specifications of these six simulations are given in table 2. To determine the sensitivity of the simulation to PBL and cumulus convection parameterization schemes, we considered the Yonsei University (YSU, Hong *et al.* 2006) PBL scheme and Mellor–Yamada–Janjic (MYJ: Mellor and Yamada 1982; Janjic 2003) PBL scheme and also the Kain (2004), Kain

and Fritsch (1993) convection scheme (KF) and Betts Miller and Janjic (Betts and Miller 1986; Janjic 1994) convection scheme (BMJ). The results of previous studies on evaluation of PBL parameterizations and customization of WRF-ARW model for the simulation of tropical cyclones had shown good performance of YSU and MYJ PBL schemes for this purpose (e.g., Nolan *et al.* 2009; Osuri *et al.* 2012; Srinivas *et al.* 2013; Chen *et al.* 2015). Osuri *et al.* (2012) and Srinivas *et al.* (2013) were conducted sensitivity experiments with PBL and convection Parameterizations using WRF (ARW) for several severe tropical cyclones formed over NIO and they found the combination of YSU PBL scheme with KF convection scheme (YKF) provides a better prediction of intensity, track, among the other combinations of physical parameterization schemes (YSU and MYJ PBL Schemes and KF, BM, and GD convection schemes).

The authors, based on previous studies in this regard, designed their sensitivity experiments with PBL and convection parameterizations using AHW model for Gonu super cyclone. The YSU (Hong *et al.* 2006) PBL scheme is known as first-order closure scheme, since it does not require any additional prognostic equations to express the effects of turbulence on mean variables. The YSU scheme takes into account non-local mixing by adding a non-local gradient adjustment term (γ_c) to the local gradient of each prognostic mean variable for heat and momentum components.

The MYJ PBL scheme is known as TKE closure (1.5 order closure) scheme. The MYJ PBL scheme applies the local mixing with the local diffusivity from the lowest to the highest vertical level for both convective and stable PBL, and there is no separation between the PBL and the free atmosphere mixing. This PBL parameterization method is explained in more detail in Janjic (1990), Mellor and Yamada (1982) and Janjic (2003) (MYJ).

The Kain (2004), Kain and Fritsch (1993) scheme (KF) uses a mass-conserving, one dimensional entraining–detraining plume model that parameterizes updrafts as well as downdrafts. Mixing was allowed at all vertical levels through entrainment and detrainment. This scheme removes convective available potential energy (CAPE) through vertical reorganization of mass at each grid point. The scheme consists of a convective trigger function (based on grid-resolved vertical velocity), a mass-flux formulation, and closure assumptions (Osuri *et al.* 2012). Betts, Miller and Janjic (Betts and Miller 1986; Janjic 1994) scheme (BMJ) is

an adjustment-type scheme that forces soundings at each point towards a reference profile of temperature and specific humidity. The scheme's structure favours activation in cases with substantial amounts of moisture in low and mid-levels and positive CAPE. The representation is accomplished by constraining the temperature and moisture fields by the convective cloud field (Osuri *et al.* 2012). The configurations and specifications of six simulations that were performed with the different combinations of PBL and convection schemes are given in table 2.

4. Results and discussion

4.1 Sensitivity experiments with model domain coverage

Figures 3(a), 4(a) and 5(a) show simulated tracks, maximum 10-m wind and minimum sea level pressure, respectively for domains D1, D2 and D3. The domain D1 covers the greater land area. At first glance, it seems this might cause the differences in the simulation of the cyclone track and intensity. As shown in these sensitivity experiments, the domain D3 had the best performance in the simulation of the cyclone track and intensity; however, the second domain could not perform at par to the third domain. Thus, it can be concluded that taking larger amounts of land or sea in domain coverage cannot be considered as a main logical reason for differences in performances. Land cover and large-scale processes play a major role in the prediction of cyclone intensity and track. Kumar *et al.* (2011) confirmed the importance of the location of domain and presented that the western boundary play a significant role in controlling the track Sidr (2007, Bay of Bengal) TC. By taking the route of TC Gonu to northwest and impact of the large-scale process (easterly winds) in the track, and moving the domains towards the east, the results improved. In domain D3, the model predicted the first landfall over Oman with only position error 9 km and time error 15 hr (delay) and the second landfall of Gonu over Iran with position error 90 km and time error 15 hr (delay) compared with IMD. The model predicted peak intensity for Gonu of about 50 m/s with time error of 15 hr (delay) with a difference of about 15 m/s than the IMD reference data. The track simulation of domain D3 had the best performance and the intensity simulation results at the time of the cyclone reaching

to the coast of Oman and Iran, were close to IMD. Even though domain 3 predicted best results for peak intensity, the scope of improvement cannot be negated. To achieve the improvement, sensitivity of the simulations to resolution is conducted with fixed and movable nests separately within this domain (domain D3).

4.2 Sensitivity experiments with horizontal resolution

Fixed and movable nesting within the domain D3 were conducted with 9 km resolution separately in fourth and fifth simulations. A dramatic improvement in results was observed for cyclone peak intensity that model predicted 61 m/s with time error 12 hr (delay) with 4 m/s difference as compared to IMD reference data (see figures 4b and 5b). The results are in concordant with the results reported by Davis *et al.* (2010), but the quality of the predicted track, especially when reaching to Oman as compared to the third simulation (domain D3 with 27 km horizontal resolution) had been reduced (see figure 3b). Model predicted the first landfall over Oman with position error 100 km and without any time error and the second landfall of Gonu over Iran almost without position error and with time error of 21 h (delay) for fixed nesting that had better performance for the track simulation than movable nesting. On third movable nest (3 km resolution), it performed two experiments, one with KF cumulus parameterization and other, without it. The removal of cumulus parameterization is based on the results of Davis *et al.* (2010) as the grid spacing decreases from around 10–4 km or less. Poor simulation results of Gonu track in this resolution were predictable according to recent studies (e.g., Goerss 2006), but simulation results of Gonu intensity also incredibly produced higher error-rate compared with reference 9 km simulation (9-km Movable Nesting) even compared with experiments on 27 km resolution. We examined numerous domains in different sizes in order to improve 3 km resolution nest results, but there were no significant improvement in simulated intensity. This result shows that improvement of horizontal and vertical resolution does not always improved simulated TC intensity (Schwartz *et al.* 2009).

It is worthwhile to mention, global and regional simulations have proved that high resolution is not a requirement for improved track prediction (Goerss 2006).

Figure 3. Simulated tracks for different sensitivity experiments. (a) Domain coverage, (b) horizontal resolution, (c) initial condition, (d) surface-fluxes parameterization on 27-km resolution, (e) surface-fluxes parameterization on 9-km resolution, and (f) PBL and convection schemes.

4.3 Sensitivity experiments with initial condition

The eighth and ninth simulations were initialized at 00 UTC 3rd June and 00 UTC 4th June with 5 and 4 days simulation length, respectively. The simulation results were compared with third simulation that had been initialized at 0000 UTC 2 June with 6 days simulation length. IMD reference data for cyclone Gonu shows values of 998, 990 and 980 hPa for the central pressure at 0000 UTC 02 June, 03 June and 04 June, respectively. As can be seen in figures 3(c), 4(c) and 5(c), whatever the initial condition of simulation be, near to peak intensity time of the cyclone, simulated peak intensity of the cyclone have been very weak as well as the simulated track that did not reach to the coast of Oman and with large differences reach on the south-east coast of Iran. This can be, as an important result that the initial condition of simulation must be prior to formation of low or at a point when the central pressure of the cyclone is experiencing almost 1000 hPa. This factor can directly affect the amount of water vapour available for latent heat release and storm intensification and allow the initial spin-up of cyclone (Davis and Bosart 2001). This result is comparable with Kumar *et al.* (2011) and Kanase and Salvekar (2011).

4.4 Sensitivity experiments with surface-fluxes parameterization

The results of simulated intensity for coarse domain with 27-km resolution and three surface-flux parameterizations during 00 UTC 02–08 June 2007 are represented in figures 4(d) and 5(d). The comparison of the Donelan–Large and Pond formulation, with less drag and steady C_k and the Charnock–Carlson and Boland formulation that have higher drag and increasing C_k with wind speed had shown that the former has higher wind speeds as well as lower central pressures. The result was obtained after 48-hr simulation, where wind speed was increased up to 78-knot and higher C_d in the Charnock–Carlson and Boland formulation cease increasing speed. With a bit of leniency, we can conclude that the effect of C_d numerical value is more than C_k in predicting TC intensity. The Donelan–Large and Pond formulation and Donelan–Garratt formulation simulated results with the same drag but different C_k in this interval indicated that where C_k in Donelan–Garratt formulation decreasing with wind speed showed lower wind speeds as well as higher central

pressures. It is noteworthy, considering the result of Emanuel (1995) for modelling prediction that the ratio of C_k to C_d in real TC lies in the range of 0.75–1.5. Davis *et al.* (2008) suggested that it must be pointed out that the real drag force on surface winds is determined by the time-evolving ocean wave spectrum, prediction of which requires a wave model (e.g., Chen *et al.* 2007). Therefore; the above-mentioned drag parameterizations should be considered as crude representations of the bulk effects of waves in TCs (Davis *et al.* 2008). The comparison of the sensitivity of simulated Gonu intensity with various surface-flux parameterizations clearly revealed that the Donelan–Large and Pond configuration have achieved significantly better simulated results on resolution 27-km grid but predicted for cyclone peak intensity with 30-knot wind speed was less compared with IMD. Then, it was conducted three simulations on resolution 9-km grid. On this resolution, the results are similar to sensitivities on the 27-km resolution, but it significantly improved the wind speed at the peak intensity as well as Davis *et al.* (2008) based on sensitivity simulations of Katrina. It means that the Donelan formulation, with less drag than the Charnock formulation, results higher wind speeds but also higher central pressures on 1.33 km resolution (figures 4e and 5e). Figure 5(e) exhibits that the central pressure simulated by Charnock–Carlson and Boland formulation is lower than Donelan–Large and Pond formulation. The results of simulated tracks did not demonstrate significant sensitivity to these surface-flux parameterizations (figure 3e).

4.5 Sensitivity experiments with PBL and convection schemes

Figure 3(f) gives the tracks of the six different combinations of PBL and convection parameterization schemes on resolution 9-km grid with movable nesting compared to IMD. The combination of MYJ PBL scheme with KF convection scheme has presented a predicted track with better quality than the other combinations. The model predicted the first landfall over Oman with position error 10 km and time error 6 hr (delay) and the second landfall of Gonu over Iran with position error 30 km and time error 21 hr (delay) for MYJ–KF combination. The results conveyed that BMJ convection scheme meaningfully predicted track accuracy. Osuri *et al.* (2012) also presented that convection schemes strongly affect the cyclone tracks;

Figure 4. Same as figure 3, but for simulated maximum 10-m wind.

however, there was no salient difference between the simulations of KF and BMJ convections. With a bit of leniency, the simulated track by YSU-KF combination placed in the next level. This combination had the best performance in the simulations of Osuri *et al.* (2012). The simulated track by

YSU-BMJ and MYJ-BMJ combinations were almost consistent with IMD in the first 3 days. After that, swerve amazingly from the IMD track and passes so far from the coast of Oman. Figures 4(f) and 5(f) give the simulated intensity of the six different combinations of PBL and

Figure 5. Same as figure 4, but for simulated minimum sea level pressure.

convection parameterization schemes compared to IMD for maximum 10-m wind and minimum sea level pressure, respectively. The YSU-KF in prediction of cyclone peak intensity had exhibited a better performance compared with other combinations; however, the MYJ-KF combination

placed in the next level of performance in the predicted track (see figure 3f) and had not an acceptable performance in prediction of intensity of the cyclone (see figures 4f and 5f). The other combinations did not provide good simulated intensity results.

Table 3. *Errors in simulated track near shoreline of Iran, Oman, the intensity at peak time, and time errors in reaching cyclone to these shorelines for each sensitivity experiments.*

Names of experiments	Iran shoreline		Oman shoreline		Peak intensity		
	Position error (km)	Time error (hr)	Position error (km)	Time error (hr)	CSLP error (hPa)	Max wind 10 m error (knot)	Time error (hr)
27 km-D1	NO L.F	–	0	– 24	– 45	+ 50	– 18
27 km-D2	NO L.F	–	90	– 30	– 35	+ 40	– 15
27 km-D3	90	– 15	9	– 15	– 25	+ 30	– 15
9 km-fixed nesting	0	– 21	100	0	– 5	+ 8	– 12
9 km-movable nesting	30	– 21	120	– 15	– 10	+ 10	– 9
3 km-movable nesting-cu 0	NO L.F	–	NO L.F	–	–	–	–
3 km-movable nesting-cu 1	NO L.F	–	110	– 30	– 50	33	30
27 km-3 June-5 days	110	– 15	NO L.F	–	–	–	–
27 km-4 June-4 days	120	– 15	NO L.F	–	–	–	–
27 km-Charnock–Carlson and Boland	90	– 15	9	– 15	– 45	+ 50	– 12
27 km-Donelan–Large and Pond	90	– 15	9	– 15	– 25	+ 30	– 15
27 km-Donelan–Garratt	10	– 15	NO L.F	–	– 35	38	– 9
9 km-Charnock–Carlson and Boland	30	– 21	120	– 15	– 10	+ 35	– 9
9 km-Donelan–Large and Pond	30	– 21	120	– 15	– 10	+ 10	– 9
9 km-Donelan–Garratt	30	– 21	120	– 15	– 15	+ 20	– 9
9 km-YSU–BMJ	NO L.F	–	NO L.F	–	–	–	–
9 km-YSU–KF	30	– 21	120	– 15	– 10	+ 10	– 9
9 km-YSU–no	30	– 21	130	– 12	– 45	+ 45	– 18
9 km-MYJ–BMJ	NO L.F	–	NO L.F	–	–	–	–
9 km-MYJ–KF	30	– 21	10	– 6	– 25	+ 35	– 30
9 km-MYJ–no	NO L.F	–	120	– 15	– 48	+ 55	– 18

4.6 Review of sensitivity experiments performance

In order to present a summary of performed simulations, table 3 shows errors in simulated track near the shore of Iran–Oman and intensity at peak point and also time errors in reaching cyclone to these points for sensitivity to domain design, starting time and horizontal resolution, surface-flux parameterizations, cumulus convection and PBL parameterization schemes, respectively.

5. Conclusion

According to the numerical-experimental results and analyses in this study, the simulated track and intensity of a supertropical cyclone could show a significant sensitivity to the domain coverage, horizontal resolution, initial condition, ocean–atmosphere surface flux parameterizations (momentum, heat and moisture), planetary boundary layer (PBL) and cumulus convection physical parameterizations. Simulations demonstrated that selective domains that was extended more to the east (D3 with 27 km resolution) with the initial condition before intense deepening of low

pressure, or in other words, when the central pressure turned around 1000 hPa, it presented satisfactory cyclone track and for intensity at reaching time to the coast of Oman and Iran had acceptable performance. Improving simulations with the initial condition before the rapid deepening of low pressure, was consistent with the result of Kanase and Salvekar (2011). When the simulation initialized after this time, the model is not able to simulate correctly the rapid intensification and thermodynamic phenomena at the future time. In other words, model needs enough time until surface fluxes of heat and moisture penetrate deeply into the troposphere in order to simulate tropical cyclone intensification and this subject was clearly observed in this study. Conducting fixed and movable nesting (9-km resolution) separately within the coarse domain, though revealing significantly improved simulated intensity accuracy, significantly reduced the quality of the simulated track. Simulated tracks in lower horizontal resolution (27 km) were better than higher horizontal resolution (9 km) that confirmed the result of Goerss (2006). Goerss (2006) had expressed that high resolution is not a requirement for

improved track prediction. Increasing horizontal resolution to 3 km incredibly reduced the simulated intensity accuracy, even weaker than 27 km resolution. This requires further studies in future. This result is uncommonly contrary to results of Davis *et al.* (2008, 2010) and should be evaluated with complementary methods for TC simulation in this region. It was also shown that the fixed nesting has better performance than movable nesting. However, it is estimated that the cost of implementing fixed nesting will be considerably more than for movable nesting, but this nesting method presented better track and intensity results in this study. It can be said that the movable nesting techniques and their performance significantly developed and improved in recent years (e.g., Fierro *et al.* 2009; Tallapragada *et al.* 2014 and ARW User's Guides 2017), but in practice, the movable nesting with respect to the less CPU processing has some advantages. It is applicable to use the results of preliminary simulations to predict the track and the results of nesting simulations to predict intensity.

A significant sensitivity of Gonu simulated intensity to the surface-flux parameterizations was also observed. The experiment with Donelan parameterization for momentum exchange and Large-Pond parameterization for enthalpy were found to be more efficient. Authors concluded that the effects of C_d is more than that of C_k in predicting of TC intensity. There are different formulations for C_d . Thus, based on the results of this study and Davis *et al.* (2008), for better considering drag coupling with a wave model can improve the results. Also, the results showed that simulated track could not be more sensitive to the surface-flux parameterizations. The difference in drag between the two drag formulations through Donelan and Charnock scheme is relatively smaller than the reality.

It was found that the AHW configurations with MYJ-PBL and KF convection schemes for track prediction and YUS-PBL and KF convection schemes for intensity prediction were satisfactory. The KF scheme produced more realistic intensity and track positions with relatively higher convective warming and stronger vertical motions in the upper troposphere relative to the other cumulus schemes, which may be due to the triggering of convection based on buoyancy in the case of the KF scheme (Srinivas *et al.* 2013). Larger eddies in YUS-PBL quickly transport surface heat to higher altitude and entrain higher

potential temperatures above the PBL incorporating a countergradient correction term into down-gradient-diffusion-caused increased intensity than MYJ-PBL. It can be mentioned that the sensitivity results of simulations to the convection and PBL parameterization schemes in this study is almost consistent with Osuri *et al.* (2012) study.

The results implicitly indicated that each particular forecast aspect of TC (e.g. track, intensity, etc.) in general will require its own special design.

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