# Sensitivity Study of Cyclone Gonu Intensity and Track to Surface Exchanges Parameterization: Advanced hurricane WRF model application

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## Abstract

Real-time forecasting errors of a tropical cyclone include 1) excessive intensification prior to landfall, 2) insufficient momentum exchange with the surface, and 3) inability to capture rapid intensification when observed. To estimate these errors, several parameterizations of surface exchanges and horizontal resolution have been designed and tested as part of what is termed the Advanced Hurricane WRF (AHW) model. In this study, Gonu tropical cyclone (2007) that it was formed in the Arabian Sea was selected. Based on sensitivity simulations of Gonu storm, the maximum wind and minimum sea surface pressure, was found to be sensitive to surface momentum exchange and model resolution. The simulated of rapid intensification in Guno was not significantly improved until the grid spacing approached 9 km and Donelan parameterization for momentum and Large and Pond parameterization for heat and enthalpy exchanges are found more efficient for this case. Also the simulated track was found to be more sensitive to model resolution.

**Key words:** Gonu, Cyclone, Intensity, AHW

## 1. Introduction

Tropical cyclones (TCs), all over the world, are recognized as the most common and most devastating of all the natural disasters. Nearly 80–90 TCs occur around the globe that about 40–50 attain intensity of 33 m/s (Frank and George, 2007). Approximately 7% of TCs originate in north of Indian Ocean and nearly 2% in Arabian Sea (WMO report, 2008).

The prediction of TC track has been on a clear path toward improvement for many years and nearly has been achieved (Elsberry, 2005). The global and regional simulations have proved that high resolution is not a requirement for improved track prediction (Goerss, 2006). The prediction of TC intensity is very complicated, because track prediction depends more on large-scale processes, and intensity depends on the inner-core dynamics and its relationship to the environment (Marks and Shay, 1998). It means that the intensity is a multiscale problem

(Goerss, 2006). Only recently has the computational capability to address multiple scales of convection (cell scale, mesoscale, and synoptic scale) been achieved. The requirement to resolve the inner core, including the eyewall, the eye, and inner spiral rainbands near the eyewall, has led to the application of models with grid lengths of only a few kilometers (e.g., Krishnamurti, 2005; Braun et al., 2006; Chen, 2006; Davis et al., 2008).

Further the importance of resolution, other key issues for TCs prediction include the effect of mixing-induced ocean-surface cooling, treatment of momentum, heat and mixture fluxes at the air–sea interface, and improvement of the initial vortex structure through data assimilation. These Allegers will be each more important when we are moving toward finer spatial resolution in simulations.

In this study, sensitivity of Gonu simulations to air–sea fluxes parameterization and model resolution are studied as key issues for improving simulation accuracy. Herein, sensitivity to atmospheric physical parameterizations such as cloud physics and the boundary layer physics that affect gonu intensity too, are not considered explicitly.

## 2. Data and Material

Gonu was strong cyclone (categury 5) that was formed in the Arabian Sea during the periods of 1-7 June 2007 .At the peak intensity, cyclones Gonu was caused 3-min sustained wind about 240 km/h and minimum pressure about 920 mb. Financial losses of Gonu cyclone was reported around 4.2 billion USD and for human casualties at least 78 persons (IMD report, 2008). Herein, we have not planned to discuss about synoptical conditions of the Gonu storm formation, and only the effects of Air-Sea interactions on intensification is interpreted.

The performance of Advance Hurricane WRF (Advanced Research Weather Research and Forecasting) model (AHW model: Davis et al., 2008) is evaluated in explicit simulations of Guno super cyclone (2007). The data from National Centre of Environmental prediction (NCEP) global final analysis (FNL) on a 1.0°×1.0° grid is 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 from NCEP/MMAB. The information of reference track for Gonu cyclone has been received from Indian Meteorological Department (IMD). The mixed layer ocean model requires specification of an initial mixed layer depth $h_0$, and a deep-layer lapse rate $\Gamma$. The ocean model was initialized with $h_0$ and $\Gamma$ equal to 50 m 0.14 in order to the NCEP Global Ocean Data Assimilation System (GODAS), when the negative feedback of wind-driven ocean mixing on hurricane intensity was planned to be considered (Davis et al., 2008).

## 3. Research Methodology

In order to implement the Gonu simulations we considered two domain, the first domain was fixed with 27-km horizontal grid resolution (with 145×110 grid points) and second domain was nested movable domain with 9-km horizontal grid resolution (with 49×49 grid points) that was configured with a two-way nesting (fig. 1). All domains had 41 vertical layers with a terrain that followed sigma coordinates with the model top at 0.5 hPa.

The surface-flux parameterizations include of both momentum and enthalpy (heat and moisture) exchange. Two main schemes for momentum exchange are presented by Charnock and Donelan (Charnock, 1955; Donelan et al., 2005) that Charnock formulation is a default scheme in mesoscale meteorological models. In Charnock formulation, roughness length given as

$$Z_{۰} = C_{z۰}\left(\frac{u_*^{۲}}{g}\right) + O_{z۰} \quad (1)$$

Where $C_{z۰} = ۰.۰۱۸۵$ and $O_{z۰} = ۱.۵۹ \times ۱۰^{-۵}$ m and frictional velocity $u_*$ defined as

$$u_* = \left(\left|\frac{\tau}{\rho}\right|\right)^{۰.۵} \quad (2)$$

Where τ is Reynolds stress (shearing stress) and ρ is air density. The relation between roughness length and frictional velocity is recursive, but the model formulations use values from the previous time step and adjusted quickly.

In atmospheric boundary layer, drag coefficient is defined as

$$C_D = \left(\frac{u_*^{۲}}{V_{۱۰}^{۲}}\right) \quad (3)$$

Where $V_{10}$ is the wind speed at 10-m height. The Charnock relation gives a 10-m drag coefficient that generally increases from about 0.001 to 0.003 at normal TC wind strengths, and it would recent to 0.005 for category 5 storms (wind >70 m $s^{-1}$). However, this estimation for category 5 storms does not match with observational evidence (e.g., Black et al. 2007) that suggests drag coefficient remains near 0.003 for high wind speeds.

Donelan is introduced a drag formulation based on the high wind speed wind-tunnel experiments (Donelan et al. 2004) that results are showed $C_d$ lower than those from the Charnock relation for low winds with a linear increase up to a maximum near 0.0024 at about 35 m $s^{-1}$. In Donelan formulation, roughness length given as

$$Z_{۰} = ۱۰\exp\left(-\frac{۱۰}{u_*^{\frac{۱}{۳}}}\right) \quad (4)$$

With a lower and upper limit on $z_0$ of $0.125\times10^{-6}$ and $2.85 \times10^{-3}$ m, respectively. The Donelan formulation, with less drag than the Charnock formulation shows yourself effects with higher wind speeds but also higher central pressures and a larger eyewall radius in strong TCs simulations. This subject needs to validate with TCs observations over all the tropical.

The exchange coefficients of heat ($C_\theta$), moisture ($C_q$) and enthalpy ($C_k$) formulate by friction velocity, scaling temperature $\theta^*$ and scaling moisture $q^*$. These scaling parameters define the similarity theory profile. The available schemes for estimation of molecular viscosity sublayer roughness length confirm an inverse relationship between roughness length and wind speed, and has the effect of a resistance to the eddy scalar transports that increases with wind speed. It means that the $q^*$ contribution to the surface moisture flux $u^*q^*$ tends to oppose the effect of $u^*$ increasing with wind speed (similarly for heat and enthalpy). The coefficients of $C_\theta$, $C_q$ and $C_k$ formulate as

$$C_\theta = u_*\theta_*/V_{۱۰}\Delta\theta \qquad C_q = u_*q_*/V_{۱۰}\Delta q \qquad C_k = C_p\theta_* + L_v q_* \quad (5)$$

Where $\Delta\theta$ and $\Delta q$ are difference in water vapor mixing ratio and potential temperature between the surface and 10-m. $C_P$ and $L_v$ are heat capacity at constant pressure and specific latent heat of vaporization, respectively.

For example, estimated exchange coefficient of enthalpy ($C_k$) during the simulations are related to selected scheme for estimation of $\theta^*$ and $q^*$. The $C_k$ will increase slowly in Carlson and Boland, stay steady in Large and Pond and decrease in Garratt parameterizations with increasing of wind speed (Carlson and Boland, 1978; Large and Pond, 1981; Garratt, 1992).

According above description, considering different schemes for different roughness lengths velocity, water vapor mixing ratio and potential temperature scaling in atmospheric surface layer over water would significantly affect estimated $C_k$ and $C_D$ and also TC intensity. For example, 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).

For this study, a series of six simulation experiments are carried out with different configuration for two horizontal grid resolution and three air–sea fluxes parameterization. The naming of six experiments with summery information about model design, initialization, and physical parameterization are given in Fig.1, Table 1 and Table 2.

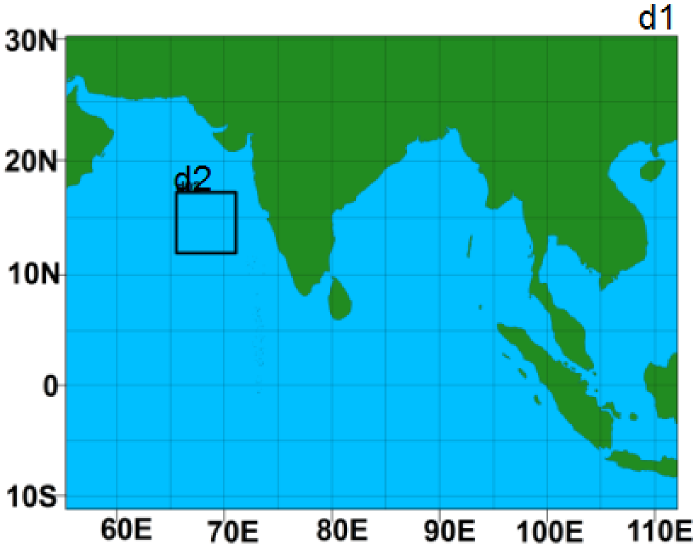

Fig.1: Geographical coverage of AHW 27-km (fixed) and 9-km (movable) domains.

| **Physical parameterization** | **Scheme** |
|---|---|
| Horizontal grid resolution | 1-27km<br>2- 9km |
| Model top | 50 hp |
| Vertical grid mesh | 41 level |
| Initial and Boundary conditions | (NCEP) global final analysis (FNL) |
| Simulation periods | 146 h |
| Nesting | 2-way |
| Shortwave radiation | Dudhia scheme (Dudhia, 1989) |
| Longwave radiation | Rapid Radiative Transfer Model (Mlawer et al., 1997) |
| Planetary boundary layer | Yonsei University (YSU) planetary scheme (Noh et al., 2003). |
| Land-surface | 5-layer thermal diffusion scheme |
| Surface momentum exchange | 1-Charnock (Charnock ,1955)<br>2-Donelan (Donelan et al. 2004) |
| Surface enthalpy exchange | 1-Carlson-Boland (Carlson and Boland, 1978)<br>2- Large and Pond (Large and Pond, 1981)<br>3- Garratt (Garratt, 1992) |
| Ocean mixed layer feedback | Active ($h_0$ and $\Gamma$ equal to 50 m 0.14) |
| Cumulus scheme | Kain–Fritsch parameterization (Kain, 2004) |
| microphysics scheme | WSM6 (Hong et al. 2004) |

Table1. Overview of the AHW model configuration used in the present study.

The model was configured by the WSM6 microphysics scheme (Hong et al., 2004), while the Rapid Radiative Transfer Model (RRTM, Mlawer et al., 1997) and the Dudhia scheme

(Dudhia, 1989) were used for the longwave and shortwave radiation calculations, respectively. The thermal diffusion scheme was used to represent surface physics with the Yonsei University (YSU) planetary boundary layer scheme (Noh et al. 2003). The simulations were conducted for 00Z 02 June 2007 to 00Z 08 June 2007 interval for Gonu.

| **Name of the Experiment** | **Resolution** | **$Z_0$ and $C_D$** | **$Z_{0q}$ and $C_K$** |
|---|---|---|---|
| 27km-Charnock- Carlson | 27km | Charnock | Carlson-Boland |
| 27km-Donelan- Large | 27km | Donelan | Large and Pond |
| 27km- Donelan- Garratt | 27km | Donelan | Garratt |
| 9km-Charnock- Carlson | 9km | Charnock | Carlson-Boland |
| 9km-Donelan- Large | 9km | Donelan | Large and Pond |
| 9km- Donelan- Garratt | 9km | Donelan | Garratt |

Table2: Naming, resolution and surface exchange parameterizations for each experiment.

## 4. Results and Analysis

In the first, the results of simulated intensity (minimum pressure and maximum wind speed) for coarse domain (Fig. 2) are analyzed. It is clearly showed that the sensitivity of simulations to the different three air–sea fluxes parameterization for simulations of Gonu at 27-km grid resolution at 0000 UTC 02 June 2007 (144-h model forecast). The Donelan-Large formulation, with less drag and steady $C_k$ than the Charnock-Carlson formulation that have higher drag and increasing $C_k$ with wind speed, results in higher wind speeds also lower central pressures. This happens after 48-h simulation where that wind speed increase until 78-knot. After this condition, high drag in the Charnock-Carlson formulation tends to oppose increasing wind speed. Comparison between Donelan-Large formulation and Donelan-Garratt simulation results with the same drag but different $C_k$ in this interval shows $C_k$ decreasing with wind speed that it tends to oppose wind speed increasing. Also Fig.2 shows steadily wind speed increase and decrease during first 48-h and last 48-h simulation for all three parameterizations for air–sea fluxes. The comparison of the sensitivity of simulated Gonu intensity with air–sea exchange parameterizations clearly showed that the Donelan-Large configuration has achieved significantly better simulated results at 27-km grid resolution but with 30-knot wind speed less than reported speed by IMD.

In order to study sensitivity of simulated Gonu intensity to horizontal grid resolution, it was conducted three experiments at 9-km grid resolution similar to last three experiments. The results were showed similar sensitivities at 27-km grid resolution but it was significantly improved the wind speed at the peak of cyclone intensity for these three air–sea exchange parameterizations (Fig. 3). Also these results showed that the central pressure simulated by Charnock-Carlson formulation, has been better compared to the 27-km resolution (as Donelan-Large formulation).

The results of simulated tracks were not significantly sensitive to these surface exchange parameterizations (not shown) but it showed more sensitivity to horizontal grid resolution (Fig.4). As can be seen in Fig. 4, the simulated track for 27-km resolution is better than the 9-km resolution that it consistent with the results of Goerss (2006). This proved that high resolution is not a requirement for improvement of track prediction.

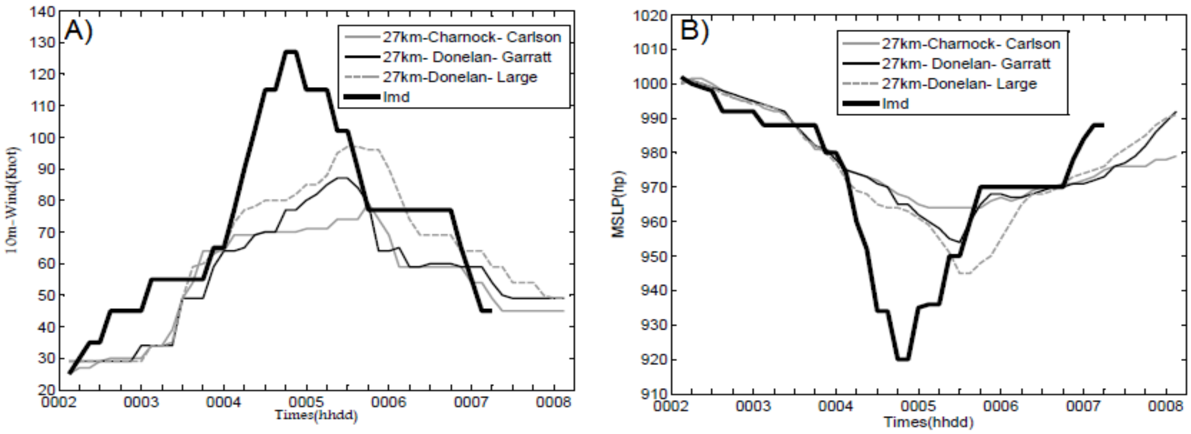

Fig. 2: (a) Maximum 10-m wind and (b) minimum sea level pressure for cyclone Gonu (at 27-km resolution with different three air–sea exchange parameterizations)

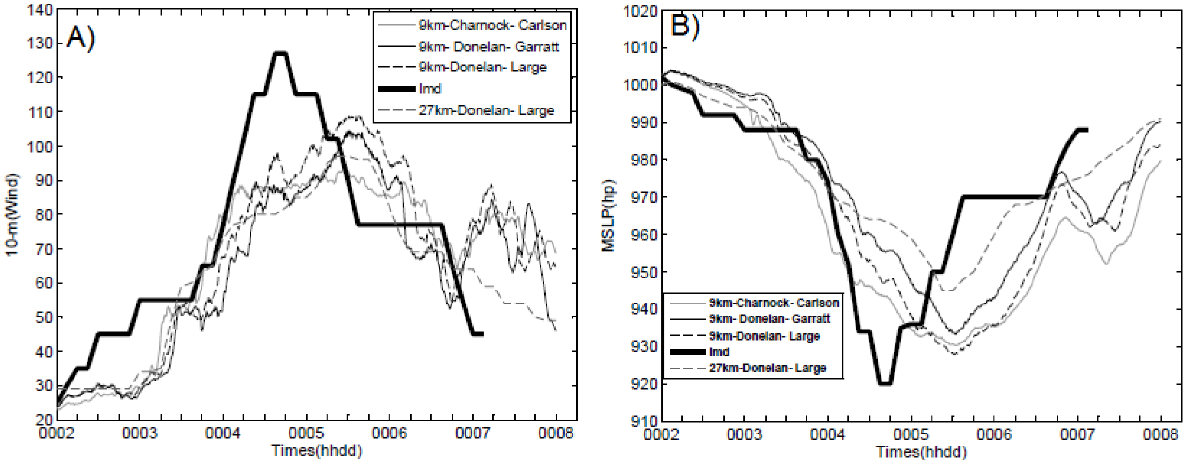

Fig. 3: As Fig. 2 but at 9-km resolution in comparison with Donelan-Large parameterization at 27-km resolution.

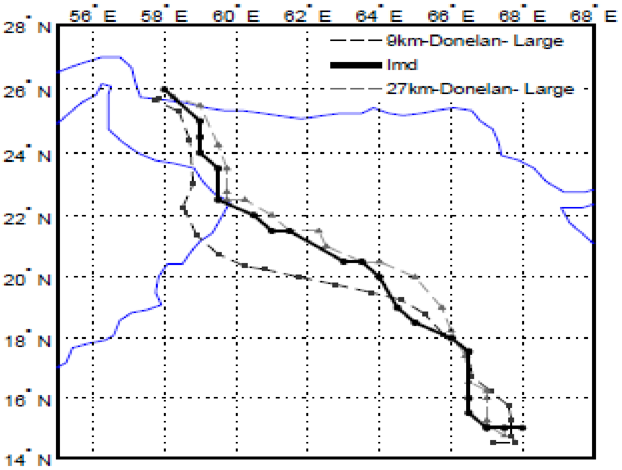

Fig. 4: Simulated tracks at 27 and 9-km resolutions during 00 UTC 02 - 00 UTC 08 June.

## 5. Conclusions

In this study, it is seen a significant sensitivity of simulated intensity of one TC to air–sea exchange parameterization and horizontal grid resolution. For selected TC, the experiment with Donelan parameterization for momentum exchange and Large and Pond parameterization for heat and enthalpy are found more efficient. Also the results showed that simulated track could be more sensitive to horizontal grid resolution than applied air–sea fluxes parameterization. The difference in drag between the two drag formulations (Donelan and Charnock) is relatively smaller than reality. 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 drag parameterizations discussed above must be considered as crude representations of the bulk effects of waves in TCs. This sensitivity of differences in the three air–sea fluxes parameterization is less than would be inferred from the dependence of maximum wind on $(C_k/C_d)^{1/2}$, derived by Emanuel (1995), While the proper wind speed dependence of $C_k$ remains a topic of active research.

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