Simulation of surface heat fluxes of Typhoon Songda (Chedeng) 2011 using WRF-ARW model

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Abstract. Heat fluxes particularly latent heat is important to drive the development, formation, and intensification of Typhoon Songda (Chedeng). The research was carried out by performing WRF ARW. Three domains with finest resolution at 3.2-km in domain three were utilized in the model. The model involved significant physics parameters, e.g., Kain-Fritsch in the cumulus scheme, Yonsei university in the PBL scheme, and WRF Single-Moment 3-class in the microphysics scheme. The analysis focused on May 26th upon mature stage of Songda (Chedeng). The result showed that the simulation of the eye, three-dimensional structure of internal wind flow, and surface heat fluxes were well-performed. The intensity of Songda (Chedeng) was represented by azimuthal velocity. It showed that the maximum wind was 72 ms⁻¹ occurred at the eye wall at critical radius of 20-km from the eye center where large portion of latent heat available in the area. Significant variation of surface sensible and latent heat fluxes were occurred between the inner and outer core. Thus, it affected to develop a strong horizontal temperature gradient which further intensify the cyclonic inward penetration into the inner core. In terms of disaster risk reduction, this study bring benefit to assist operational weather forecaster to produce good short-range forecasts of the Typhoon intensities. If the surface heat fluxes increase gradually, early warning system on typhoon intensities that will affect over particular region is then released.

1. Introduction

Heat exchange between ocean and atmosphere is often characterized by sensible and latent heat transfer. Sensible heat usually contributes to either increasing or decreasing atmospheric temperature. Latent heat, on the other hand, takes form as evaporation and is a source of continuous hidden heat transfer as a result of water vapor condensation. Latent heat then becomes among primary energy to drive the intensification of Tropical Cyclone (TC) [1]. The mature TC intensity is typically described by axisymmetric distribution of azimuthal velocity from inner to outer structure [2, 3]. The stronger circulation is mostly found in the eye wall where latent heat is abundant in the area. Thus, the eye wall is known as the most intense zone in TC. Circulation in the eye wall might influence a positive feedback to strengthen TC since it provides moisture supply into the system.

An effort to study the relationship between TC intensity and heat fluxes had been done [4]. He constructed an idealized, steady-state model of mature TC to investigate the maintenance of TC
associated with oceanic heat transfer. In recent published paper, he developed the latest theoretical concept based on numerical simulation to study the intensification of TC controlled by surface fluxes \cite{5, 6}. Another numerical study has been done by using a coupled hurricane-ocean model to examine the ocean effect (involving the calculation of surface heat fluxes) on TC intensity \cite{7}. The utilization of a numerical weather prediction model such as earlier version of Weather and Research Forecasting (WRF) to study surface heat fluxes on TC intensity was done by testing two Planetary Boundary Layer (PBL) scheme to obtain a better simulation of latent heat fluxes. Meanwhile, in the present paper, Advanced Research WRF (hereafter refer to WRF ARW) with state-of-the-art of atmospheric simulation is applied in the model to obtain a better simulation of Typhoon Songda (Chedeng) (refer to TSC) surface heat fluxes.

Typhoon Songda (called Chedeng in the Philippines) occurrence over western North Pacific Ocean was chosen as a case study in the present paper. TSC, local name of TC, was the fourth named TC of the 2011 Northern Hemisphere tropical season. It was the most devastating storm to strike western North Pacific Ocean for the period of 2011. TSC lasted for almost two weeks from May 18th to 30th, 2011 and enhanced to reach peak activity of powerful category 5 Super Typhoon between May 24th and 26th. Low pressure area was centered nearby off west coast of Manila. The exhibition of mature Songda (Chedeng) as well as the fact that Songda (Chedeng) is not a subject of exploration yet soon motivates the study. Therefore, the present study attempt to show the roles of heat fluxes to maintain mature TC intensity by utilizing WRF model.

2. Material and Methods
The domain of study areas is between 10˚N - 20˚N and 120˚E - 130˚E for period of mature stage of TSC. The research was carried out by performing WRF ARW model version 3.3. WRF ARW is a non-hydrostatic model with terrain-following in the vertical-sigma coordinate. A review of mathematics, physics, dynamics, and thermodynamics of the model can be found in Skamarock et al. \cite{8}. In the meantime, three domains were employed in the model as shown in figure 1. Large-scale domain 1 and 2 consist of 100 x 107 and 187 x 241 horizontal grids and cover spatial resolution of 28.9-km and 9.6-km, respectively. Domain 3 consists of 247 x 259 horizontal grids at finest 3.2-km resolution. Domain 3 was utilized to analyze the result. Besides, 28 pressure levels ranging from 1000-100 hPa were employed in the model. The model was also supported by following physics parameterization: (a) surface and Planetary Boundary Layer (PBL) scheme, (b) cumulus scheme, and (c) microphysics scheme. List of physics parameterization used in the model was given in Table 1. Similar parameterization was also adapted by Osuri et al. \cite{9} to simulate different TC over north Indian Ocean. The subroutine to calculate heat and moisture fluxes from the surface was included in the model. The initial boundary condition in the model are: (a) 30 second (0.925-km) resolution of USGS terrain height data, (b) 30 second (0.925-km) resolution of global 24-category USGS land use/cover data, and (c) 1.0˚ latitude x 1.0˚ longitude grids NCEP Final Analysis (FNL) data with grib2 format. The description of the data are as follows: (a) temporal resolution of 6-hourly (0000, 0600, 1200, and 1800 UTC) dataset, (b) pressure levels are available from 1000 to 10 hPa, and (c) variables include surface pressure, sea-level pressure, geopotential height, temperature, sea surface temperature, soil values, ice cover, relative humidity, zonal and meridional velocity, vertical velocity, vorticity, and ozone concentration. The selected simulation days are from May 25th to 27th, 2011 when Songda (Chedeng) turn into category 5 Super Typhoon. Analysis will focus on second day on May 26th.

| Table 1. Physics of WRF ARW model used in the study. |
|------------------------------------------------------|
| Physics categories       | Scheme                                      |
|--------------------------|---------------------------------------------|
| Surface layer            | Monin-Obukhov with Carston-Boland viscous sub-layer |
| Land surface             | Noah land surface model                      |
| PBL                      | Yonsei university PBL                        |
| Cumulus parameterization | Kain-Fritsch scheme                          |
| Longwave radiation       | Rapid Radiative Transfer Model (RRTM) scheme |
3. Results and Discussion

The simulation of the spiral clouds and the internal structure of winds flow of TSC were shown in figure 2. The whirling clouds were counter-clockwise since it established in the Northern Hemisphere. The eye featuring the core of TSC was well-simulated as shown in figure 2a. The eye of TSC was reported to have minimum Sea-Level Pressure (SLP) of 920 hPa. The relative calm condition at the center was main feature of the eye. Another feature was typically recognized by subsidence of winds as shown in figure 2b. In the eye, the air gradually sanked and heated by compression. Thus, it was responsible for warming the zone. As a result, the eye is also well-known as the warm core.

Halverson et al. [10] in their observational study found that maximum temperature anomaly in the warm core was 11°C near 500 hPa with minimum SLP and wind speeds of 969 hPa and 54 m s⁻¹, respectively. However, their finding was lower than energetic TC shown in Hawkins and Imbembo [11]. In field study conducted by them to investigate TC Inez in 1966, the maximum temperature anomaly at the same level was 16°C with central SLP of 927 hPa. These differences might refer to the differences of size distribution on two TCs. On the other hand, the subsidence in the eye led to cloudless condition characterized by clear appearance of the sky.

Surrounding the eye was the eye wall of TSC, here the typical TC characteristics appeared. The eye wall was the most devastating zone in Songda (Chedeng) since the strongest winds usually occurred in the zone. Songda (Chedeng) had maximum sustained winds of 72 ms⁻¹. Willoughby et al. [12] and Black and Willoughby [13] found that the eye wall was a well-defined wind maximum area. It can be explained that the decreasing pressure toward the core produced a steep pressure gradient. Consequently, it caused the velocity of inward curving winds to increase. The conservation of angular momentum was behind the acceleration. As the rotation of Songda (Chedeng) was identified by convergence of wind into low pressure center, angular momentum associated with Earth’s rotation was concentrated into angular momentum associated with Songda (Chedeng) wind. When the inward of warm, moist surface air moved toward the core, it turned upward and rise in a circle of Cumulonimbus towers as shown in figure 2b.

In addition, the eye wall of Songda (Chedeng) implied the occurrence of the intense convective activity. McNoldy [14] found that strong convection might even form three eye walls during the intensification of TC. Meanwhile, outer structures of TSC were associated with spiral rainbands as shown in figure 2a. Spiral rainbands consisted of convective clouds with updrafts were found on the...
inward side of the band axis and downdrafts were located just outside the inward. At the top of the Typhoon, the flow was outward, leaving the center of the storm. Thus, it allowed the air at the surface to flow inward. Upper and lower level flow were in the opposite direction as shown in figure 2b. Both eye wall and spiral rainbands shown in figure 2a were called zone of deep convection. Houze [15] explained that in addition to contributing TC genesis, deep convection has intense updrafts but weak downdrafts as proved by the present study. Furthermore, the spinning flow of rainbands was essential to provide fuel to develop the storm since it provided moisture to get into the eye wall of Songda (Chedeng). Nevertheless, according Hack and Schubert [16], it also contributed to the release of latent heat away from the center, reducing TC intensity. Wang [17] found that the existence of strong spiral rainbands might limit TC intensity. He also concluded that cooling in the spiral rainbands maintained the intensity and the size of TC while heating maked the intensity to decrease but to increase the size of TC.

![Figure 2](image_url)

**Figure 2.** Simulation of Category 5 Super Typhoon Songda (Chedeng) at 1700 UTC on May 26th, 2011, a) swirling shape of clouds, b) three-dimensional structure of wind circulation inside the storm. Bar chart in the left in figure 2b indicates the magnitudes of wind speeds in ms\(^{-1}\) (not the terrain profile in the lowest background).

Figure 3 showed the distribution of azimuthal velocity of TSC in the boundary layer. The diameter of the eye was about 200-km in width. The velocity sharply decreased leading to light wind in the area. The decrease of azimuthal wind at the eye during mature stage of TC is often characterized by V-shaped of axisymmetric structure. As already discussed above that the maximum velocity of 72 ms\(^{-1}\) occurred at the outside edge of Songda (Chedeng) eye wall at critical radius of 20-km as shown in figure 3. The velocity gradually decreased towards spiral rainbands and outer structure of Songda (Chedeng). Stern and Nolan [18] inspected some TCs and found different critical radius of maximum wind nearby the inner core. From figure 3, it was shown that Songda (Chedeng) had approximately 200-km in radial distance from the center of the eye to outer structure of Songda (Chedeng).
Figure 3. Simulation of West-East vertical structures of azimuthal velocity (ms⁻¹) at Category 5 Super TSC at 1700 UTC on May 26th, 2011.

Figure 4. Simulation of surface heat fluxes of TSC at 1700 UTC on May 26th, 2011, a) sensible (or upward heat flux), b) latent heat flux. Both Units in Wm⁻².

The greatest wind speeds in the eye wall related to higher amount of surface latent heat flux in the area as shown in figure 4b. Mark [19] found that high quantities of latent heat release were concentrated in the eye wall. From figure 4b, it is demonstrated that just outside of the eye, surface latent heat flux reached 1400 Wm⁻². Meanwhile, at the core and the edge of the eye wall, latent heat flux at the surface slowly decreased from 1200 down to 1000 Wm⁻². In addition, surface latent heat flux in spiral rainbands and outer structure fell to 800 Wm⁻² and 600 Wm⁻², respectively. Compared to sensible heat (or upward heat flux at surface) as shown in figure 4a, latent heat flux from the ocean was three times greater than sensible heat flux. Principally, the reason for this is that most of energy
transfer released from the ocean to the atmosphere is exchanged to latent heat. It can bring to a close understanding that latent heat flux plays a major role on Songda (Chedeng) intensity than sensible heat flux. Sensible heat flux at the surface is defined as conductive heat flux from the Earth's surface to the atmosphere indicated by positive values. Moreover, heat energy transfer from the atmosphere to the ocean is indicated by negative values. The highest energy transfer occurred at the center of the eye wall reached 350 Wm\(^{-2}\). Additionally, surface sensible heat flux directly influenced Songda (Chedeng) temperature. With the exception of the eye, it further implied that higher sensible heat flux might reflect higher temperature in the same occasion. For that reason, the warm and cool region of Songda (Chedeng) occurred at the eye wall and spiral rainbands, respectively. Consequently, it increased temperature gradient and strengthened Songda (Chedeng). In conclusion, from figure 4a-b, it was depicted that surface sensible and latent heat fluxes between the eye wall and spiral rainbands showed much higher differences. Therefore, as discussed before, it might have led to the strong development of horizontal temperature gradient which further drives the formation and intensification of cyclonic circulation of into the inner core Songda (Chedeng) as shown in figure 2b. Black and Holland [20] provided a thorough aircraft study and found that strong horizontal advection might enhance the inward penetration. Overall, figure 4a and b showed that fluxes production was maximized at the eye wall. Hence, the reason behind the destructive part of Songda (Chedeng) becomes obvious since moisture transport from the ocean was greater in the area. In terms of disaster risk reduction, this study bring benefit to assist operational weather forecaster to produce good short-range forecasts of the Typhoon intensities. If the surface heat fluxes increase gradually, early warning system on typhoon intensities that will affect over particular region is then released.

4. Concluding remarks
WRF ARW model was performed to simulate the surface heat fluxes of TSC. The counter-clockwise spinning clouds featuring the eye as well as wind circulation structure inside Songda (Chedeng) were well-simulated. The simulation of subsidence of wind at the core of Typhoon Songda was well-observed. The greatest winds of 72 ms\(^{-1}\) arise at the eye wall of Songda (Chedeng). The reason behind this was the sharp pressure gradient as the decrease of pressure into the core led to accelerate the inward rotational wind. The entering wind at the eye wall was deepened by conservation of angular momentum associated with Earth’s coriolis force. As the innermost of warm, moist surface air circulates headed for the core, it rises aloft at the top of anvil clouds. Strong updrafts were observed in the spiral rainbands whereas weak downdrafts occurred just outside of updrafts in the spiral rainbands. At the top of Songda (Chedeng) boundary layer, the flow travelled away from storm center and provided a sufficient space to the inward surface flow. The illustration of azimuthal velocity obviously showed the emergence of maximum velocity at critical radius of 20-km from the eye center. However, the slope of velocity decline exponentially as the radius away. In accordance with category 5 Super Typhoon, it is also reported that the Songda (Chedeng) had 200-km in radius. From the heat fluxes simulation, it is shown that latent heat flux at the surface was three times larger than sensible heat flux. The greatest proportion of latent heat was deposited at the eye wall of Songda (Chedeng). Large in number of latent heat flux is among critical factor that trigger the strong cyclonic velocity at the eye wall. On the other hand, sensible heat flux at the surface organized Songda (Chedeng) temperature, sufficient energy transport from the ocean to the atmosphere was also maximized at the eye wall. Variation in number of heat fluxes observed between inner and outer structure stimulate to enlarge a strong temperature gradient which further strengthen the rotational of inward penetration in Songda (Chedeng). For that reason, the role of surface heat fluxes in determining Songda (Chedeng) intensity become more apparent to address.

Acknowledgments
The author expresses gratitude to Prof. Dr. Ahmad Bey for the discussion, Mr. A Fachri Radjab for giving an opportunity to carry out the study at Tropical Cyclone Warning Center BMKG, Mr. Zainal Abidin for kind assistance throughout WRF simulation, and anonymous reviewers for comments. Thankful was also addressed to DIKTI for providing financial support to the study.
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