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The efficiency of the Weather Research and Forecasting (WRF) model for simulating typhoons

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Abstract. The Weather Research and Forecasting (WRF) model includes various configuration options related to physics parameters, which can affect the performance of the model. In this study, numerical experiments were conducted to determine the best combination of physics parameterization schemes for the simulation of sea surface temperatures, latent heat flux, sensible heat flux, precipitation rate, and wind speed that characterized typhoons. Through these experiments, several physics parameterization options within the Weather Research and Forecasting (WRF) model were exhaustively tested for typhoon Noul, which originated in the South China Sea in November 2008. The model domain consisted of one coarse domain and one nested domain. The resolution of the coarse domain was 30 km, and that of the nested domain was 10 km. In this study, model simulation results were compared with the Climate Forecast System Reanalysis (CFSR) data set. Comparisons between predicted and control data were made through the use of standard statistical measurements. The results facilitated the determination of the best combination of options suitable for predicting each physics parameter. Then, the suggested best combinations were examined for seven other typhoons and the solutions were confirmed. Finally, the best combination was compared with other introduced combinations for wind-speed prediction for typhoon Washi in 2011. The contribution of this study is to have attention to the heat fluxes besides the other parameters. The outcomes showed that the suggested combinations are comparable with the ones in the literature.

1 Introduction

Numerical weather forecasting models have several configuration options relating to physical and dynamical parameterization; the more complex the model, the greater variety of physical processes involved. For this reason, there are several different physical and dynamical schemes which can be utilized in simulations. However, there is controversy surrounding any perceived advantage of one particular scheme over others. Therefore, it is critical that the most suitable scheme be selected for a study. A variety of studies have been conducted around the world in order to find the best scheme options for different fields of study (Kwun et al., 2009; Jin et al., 2010; Ruiz et al., 2010; Mohan and Bhati, 2011).

Yang et al. (2011) studied wind speed and precipitation variations during typhoon Chanchu, which occurred in the South China Sea in 2006. They carried out five different experiments using the PSU/NCAR (Pennsylvania State University/National Center for Atmospheric Research) mesoscale model (MM5), with variations in the physical parameterizations used and in sea surface temperature (SST) distributions. The simulations obtained were then compared with satellite observations.

Ardie et al. (2012) performed four types of cumulus parameterization schemes in the WRF model for simulating three events of intense precipitation over the southern Peninsular Malaysia in the winter monsoon of 2006–2007. The results were compared with the 3 hourly satellite data using a confirmation method called the “acuity–fidelity”. The four different schemes were the new Kain–Fritsch (KF2), the Betts Miller Janjic (BMJ), the Grell–Devenyi ensemble (GD), and the older Kain–Fritsch (KF1). While the BMJ scheme indicated good achievement in the second and third events, it showed high errors in the first event. The GD, KF2, and KF1 schemes executed weakly, and the BMJ and GD schemes simulated higher values for rainfall. In general, they stated that, although the BMJ scheme had good results, its feeble performance for the first event suggested that appropriateness of the cumulus parameterization scheme might be case dependent.

Li (2013) studied the effect of different cumulus schemes in simulating typhoon track and intensity. The simulation of 20 typhoon cases from 2003 to 2008 represented that cumulus schemes were really effective on the typhoon track and intensity. It was found that the KF scheme obtained the most severe typhoon, while the GD and BMJ schemes simulated weaker typhoons. Those differences were due to variation in precipitation computations. Different cumulus schemes caused dissimilar typhoon tracks in the case of large-scale circulations simulating. The results also indicated that different atmosphere vertical heating created different typhoon intensity. Those variations led to different convections that create several Latent Heat Flux (LHF) and cumulus precipitation. The KF scheme simulated the most severe vertical convection, higher cumulus precipitation, and superior intensity, while the GD and BMJ schemes generated more feeble convection, low cumulus precipitation, and less intensity.

Angevine (2010) presented that Mellor Yamada Janjic (PBL and surface layer) with a combination of 5-layer thermal diffusion (land surface), Eta (microphysics), RRTM (long-wave radiation), Dudhia (shortwave radiation), KF (cumulus parameterization) showed small differences in assessing important parameters like SST and LHF, when PBL and surface layer changed to TEMF.

Chandrasekar and Balaji (2012) also investigated the sensitivity of numerical simulations of tropical cyclones to physics parameterizations, with a view to determining the best set of physics options for prediction of cyclones originating in the north Indian Ocean. In another study by Mandal et al. (2004), the sensitivity of the MM5 model was investigated, with respect to the tracking and intensity of tropical cyclones over the north Indian Ocean. The authors identified the set of physics options that is best suited for simulating cyclones over the Bay of Bengal.

This paper is an attempt to use a variety of physics parameterization options from the WRF model to investigate the performance of this same model in predicting selected parameters, with simulations relating to typhoon Noul in the South China Sea.

1.1 WRF model overview

The WRF (version 3.3.1), a high resolution mesoscale model, was utilized in this study. This model is a next-generation numerical model for weather prediction of mesoscale processes. It was developed by the Mesoscale and Microscale Meteorology Division of the National Centre for Atmospheric Research (NCAR/MMM), in collaboration with other institutes and universities. Michalakes et al. (2004) and Skamarock et al. (2005) exhaustively explained the equations, physics parameters, and dynamic parameters available in the WRF model. The model provides different physical options for a boundary layer phenomenon such as microphysics, longwave and shortwave radiation, cumulus parameterization, surface layer, land surface, and planetary boundary layer.

A complete description of the physics options available in WRF model was developed by Wang et al. (2010). Each physics option contains different schemes and the details of all schemes have been comprehensively explained by Skamarock et al. (2005).

1.2 Case study: typhoon Noul

Typhoon Noul formed in November 2008 in the South China Sea (Fig. 1). At first, a tropical disturbance was generated in the Philippines (east of Mindanao) on 12 November. Later, on that same day, the Joint Typhoon Warning Centre (JTWC) estimated that the recorded disturbance had the potential to generate a significant tropical cyclone in the subsequent 24 h. The system was reclassified to a tropical depression from a tropical disturbance on 14 November. It was then reclassified as a tropical storm at 06:00 UTC on 16 November, and it reached its maximum point at 00:00 UTC on 17 November, with a 993 mbar minimum central pressure and maximum sustained winds of 74 km h^{-1}. Noul was slightly weakened after it made landfall in Vietnam, almost around the middle of the day on 17 November, and finally disappeared at the end of that day near Cambodia (JTWC, 2008).

2 Materials and methods

Final analysis 6-hourly data sets (FNL) with a resolution of 1°, obtained from the National Centres for Environmental Prediction (NCEP), were inserted to the WRF model as initial and boundary conditions. It should be noted that the wind speed at the 10 m level above the earth's surface is referred to as "wind speed" throughout this paper. All schemes utilized in this study are summarized in Table 1. Herein, a total of six simulations were carried out. The first simulation used the default set of schemes. The outputs were compared with the Climate Forecast System Reanalysis (CFSR) data by Saha et al. (2010), referred to as control data. The CFSR data set has variety data in different resolutions, but the study considered that which has the nearest resolution (0.5° in longitude and latitude) to the WRF resolution. The simulation period was every 4 days.

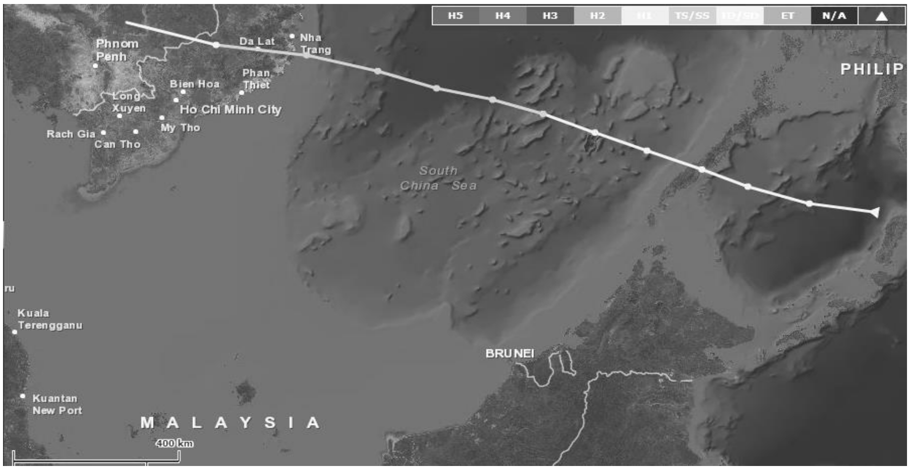

Figure 1. Typhoon Noul trace in November (NOAA, 2008).

Table 1. Different simulations conducted in the study, using various combinations of schemes.

Sim	Microphysics	Longwave radiation	Shortwave radiation	Surface layer	Land surface	Planetary boundary layer	Cumulus parameterization
1	WRF single Moment 3-class	RRTM	Dudhia	MM5	Noah	Yonsei University	Kain Fritsch
2	Eta	GFDL	GFDL	Eta	Noah	Mellor Yamada Janjic	Betts Miller Janjic
3	New Thompson	RRTM	Goddard	MM5	5-layer thermal diffusion	Yonsei University	New Simplified Arakawa Schubert
4	Stony Brook University	New Goddard	New Goddard	Eta	5-layer thermal diffusion	Mellor Yamada Janjic	Tiedtke
5	Lin et al. (1983)	RRTM	Goddard	Pleim Xiu	Pleim Xiu	ACM2	Kain Fritsch
6	Lin et al. (1983)	RRTMG	RRTMG	TEMF	RUC	TEMF	Betts Miller Janjic

WRF single Moment 3-class (Hong et al., 2004); Eta (Rogers et al., 2001); New Thompson (Thompson et al., 2008); Stony Brook University (Lin and Colle, 2011); Lin et al. (1983); RRTM and RRTMG (Mlawer et al., 1997); GFDL (Rahmstorf, 1993); New Goddard (Tao et al., 2008); Goddard (Tao and Simpson, 1993); Dudhia (Dudhia, 1989); MM5 (Menéndez et al., 2011); Pleim Xiu (Gilliam and Pleim, 2010); TEMF (Wang et al., 2010); Noah, 5-layer thermal diffusion, RUC (Wang et al., 2010); Yonsei University (Hong et al., 2006); Mellor Yamada Janjic (Janjic, 1994); ACM2 (Pleim, 2007); Kain Fritsch (Kain, 2004); Betts Miller Janjic (Betts and Miller, 1986; Janjic, 1994); New Simplified Arakawa-Schubert (Han and Pan, 2011); Tiedtke (Tiedtke, 1989; Zhang et al., 2011).

The physics options of the WRF were altered in different experiments, to see which of those is most suited for accurate analysis of the interaction between typhoon intensity and the parameters mentioned earlier. The capability of predicting typhoon intensity was investigated with the model. Furthermore, according to Wang et al. (2010), the SST-update and SST-skin functions must be activated in the model configuration (prior to version 3.4) in order to see SST variations during all simulations. The simulations were selected based on heat transfer in the surface boundary layer and on surface disturbances.

2.1 Model domains

Figure 2 indicates the defined domains for modelling. The parent domain called d01, with spatial resolution of 30 km,

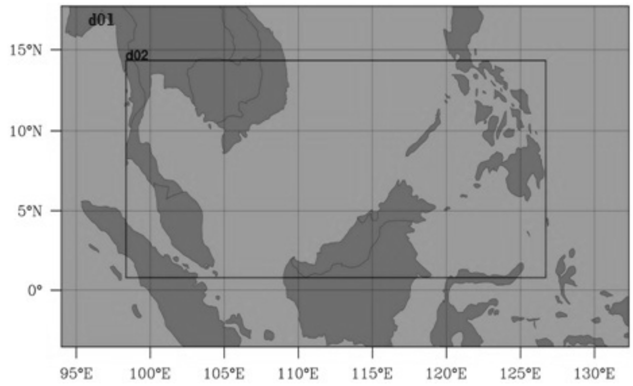

Figure 2. Model domains.

covers a bigger region than the study area. The nested domain, d02, with resolution of 10 km, includes the South China Sea, which is the region under study in this analysis. Geographically, it covers the west side of the tropical Pacific Ocean. The two domains are centred at 7° N and 113° E. The South China Sea is bounded by South China, Peninsular Malaysia, Borneo, the Philippines, and the Indo-China Peninsula (Ho et al., 2000).

2.2 Evaluation of the model

The most widely used statistical indicators in the literature dealing with environmental estimation models are root mean square error (RMSE), coefficient of correlation (CC), mean bias error (MBE), and t statistic (Jacovides and Kontoyiannis, 1995). These were used in this study for assessing model performance. These values were calculated for selected parameters, namely SST, latent heat flux (LHF), sensible heat flux (SHF), precipitation rate, and wind speed in the center of a typhoon.

The RMSE provides information on the short-term performance of a model by comparing the simulated values and the control data. The smaller the RMSE value, the better the model's performance. The MBE provides information on the long term performance of a model. A positive value gives the average amount of over-estimation in the estimated values, and vice versa in the case of a negative value. The smaller absolute value of MBE shows the better model performance. In order to evaluate and compare all of the parameters computed by the model, one can use different statistical indicators. The MBE, which is extensively used, and the RMSE, in combination with the t statistic, are being proposed in this case. The t statistic should be used in conjunction with the MBE and RMSE errors to better evaluate a model's performance (Jacovides and Kontoyiannis, 1995). The smaller value of t indicates the better performance of the model. The CC as a statistical parameter was used in this paper as well. Higher CC values show better performance of the model.

Table 2. Statistical evaluation of different simulations for SST.

	Sim 1	Sim 2	Sim 3	Sim 4	Sim 5	Sim 6
RMSE	0.71	0.86	0.91	0.71	0.72	**0.65**
CC	−0.06	**0.31**	−0.1	0.15	−0.12	−0.16
MBE	0.11	−0.28	−0.25	−0.16	−0.10	**−0.01**
t statistic	0.38	0.84	0.7	0.57	0.35	**0.06**

The best number for each statistical parameter is written in bold.

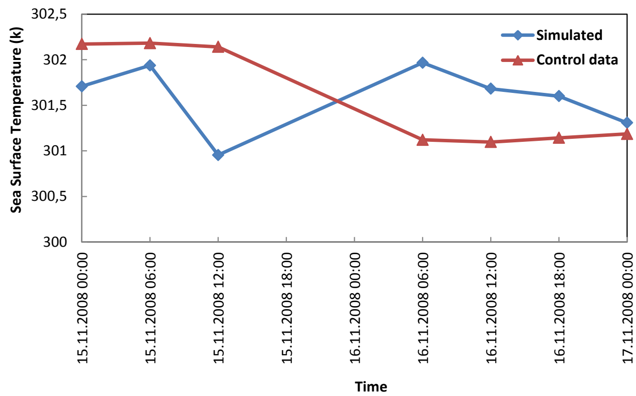

Figure 3. Comparison of best model performance (simulation 6) with control data, for 6-hourly SST prediction during typhoon Noul.

2.3 Verification process

After selecting the best simulation for each parameter in the case of typhoon Noul, the solutions were evaluated by running the model for seven other typhoons, Peipah in 2007, Tropical Depression 01W in 2008, Kujira in 2009, Chan-Hom in 2009, Nangka in 2009, Songda in 2011, and Washi in 2011. The aim was to confirm the scheme selection processes for each parameter. The typhoons were selected from all storm track data set by Knapp et al. (2010).

3 Results and discussions

The data used for validation of the variables was derived from the CFSR data set and is available on the related website (Saha et al., 2010). The results from the nested domain were used for purposes of analysis and comparison.

3.1 Sea-surface temperature

Statistical evaluation of SST is presented in Table 2. The best result of the SST simulation is shown in bold. It can be noted that simulation 6 works satisfactorily for SST, because all criteria are met, with the exception of the CC value, which was lower than expected.

Figure 3 indicates the diurnal variation of control data and simulated SST in simulation 6, with data given for every 6-h period over the study duration. By and large, there is a general tendency towards over-prediction of SST when the

Table 3. Statistical evaluation of different simulations for LHF.

	Sim 1	Sim 2	Sim 3	Sim 4	Sim 5	Sim 6
RMSE	**95.75**	115.2	112.6	140.8	143.9	168.9
CC	**0.69**	0.49	0.61	0.21	0.51	0.53
MBE	**−2.96**	13.39	−22.67	31.56	−49.65	−16.28
t statistic	**0.15**	0.59	1.04	1.17	1.87	0.49

The best number for each statistical parameter is written in bold.

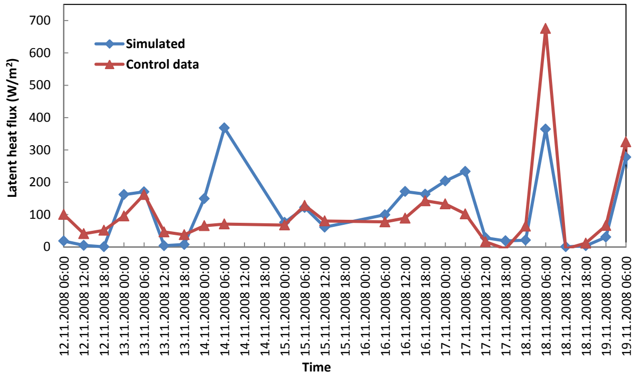

Figure 4. Comparison of best model performance (simulation 1) with control data, for 6-hourly LHF prediction during typhoon Noul.

typhoon is stronger, and under-prediction when the typhoon is weaker.

The spotlight of simulation 6 was the amount of temperature and moisture in the different atmospheric layers that were connected (Liu et al., 1997). Thus, this combination could predict SST satisfactorily, comparing to the other groups in this paper.

3.2 Latent heat flux

The oceanic LHF is heat energy released or absorbed by the ocean during a phase transition without a change in temperature, such as water-surface evaporation (Clark, 2004).

As shown in Table 3, simulation 1 performs best for LHF prediction, with the minimum RMSE, MBE, and t values, and the maximum amount of CC.

Figure 4 shows a comparison of simulated and control data for LHF in the case of the best performing simulation. Although there are some over-prediction and some under-prediction points, it can be seen that most simulated values are very close to the control values.

In this study, the simulation number 1 has focused on the different water phases in clouds. Phase changing in the different layers can affect the amount of LHF (Zhu and Zhang, 2006).

Table 4. Statistical evaluation of different simulations for SHF.

	Sim 1	Sim 2	Sim 3	Sim 4	Sim 5	Sim 6
RMSE	58.37	30.89	60.71	64.48	**23.69**	54.62
CC	0.60	0.88	0.72	−0.02	**0.93**	0.524
MBE	−12.85	−9.25	−22.38	−7.77	**0.48**	−14.38
t statistic	1.15	1.6	2.02	1.77	**0.03**	1.39

The best number for each statistical parameter is written in bold.

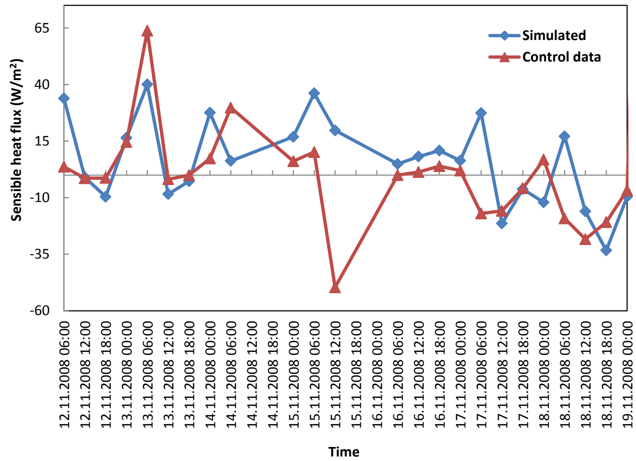

Figure 5. Comparison of best model performance (simulation 5) with control data, for 6-hourly SHF prediction during typhoon Noul.

3.3 Sensible heat flux

SHF is heat energy transferred by conduction and convection at the atmosphere–ocean interface that creates a change in the system temperature (Clark, 2004).

As shown in Table 4, of the six simulations, number 5 can strongly predict the SHF values with the highest value of CC (0.93).

The result of simulation 5, indicating its superior performance over others, is shown in Fig. 5. Almost all increasing and decreasing SHF values are predicted as well.

3.4 Precipitation rate

In the case of the precipitation rate, simulation 5 was the best-performing simulation, with consistently lowest RMSE, MBE, and t values, and the highest CC values, as shown in Table 5.

The simulated data from simulation 5 are compared with control data in Fig. 6. The results indicate that forecasts of precipitation rates before and after the typhoon are close to those of the control data. During the period of 14 to 17 November, the simulated data values for the typhoon were lower than the control data.

As a result, the simulation number 5 could estimate both SHF and precipitation rate better than the other sets. This

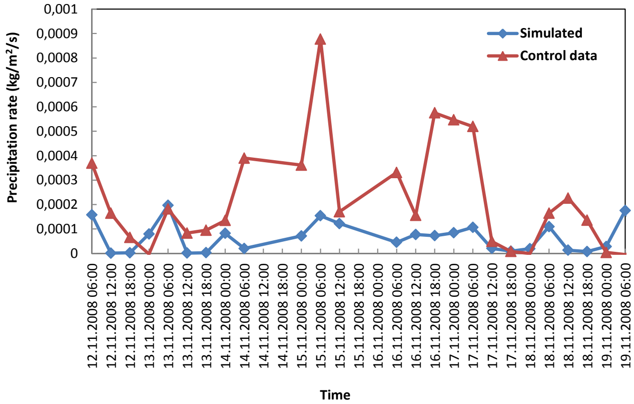

Figure 6. Comparison of best model performance (simulation 5) with control data, for 6-hourly precipitation rate prediction during typhoon Noul.

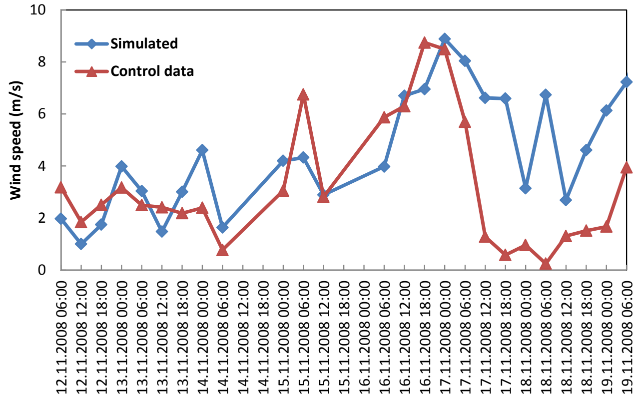

Figure 7. Comparison of best model performance (simulation 4) with control data, for 6-hourly wind-speed prediction during typhoon Noul.

combination has considered convection, mass flux, and cloud effects. Furthermore, Li (2013) demonstrated that the KF cumulus parameterization could create the most severe vertical convection.

3.5 Wind speed

Wind-speed estimations during the typhoon were statistically evaluated, as shown in Table 6. In spite of simulation 4 having low CC values, RMSE, and MBE, values are lower in comparison with those obtained in other simulations, and this simulation therefore shows the best performance for wind-speed prediction. Moreover, simulation number 4 focuses on mixed phase and multiband efficiency, along with the temperature, and the turbulent kinetic energy played a significant role in forecasting wind speed. According to Draxl et al. (2010), turbulent kinetic energy can perform well in predicting wind speed.

A general tendency for the model to over-predict wind speed was noted in all simulations, and was also observed in many earlier studies (Hanna et al., 2010; Ruiz et al., 2010). Figure 7 shows the comparison between simulated wind speed and related control data. As noted in earlier studies, wind speed is significantly affected by local fluctuations, especially in highly unstable conditions. Thus, wind sensitivities tend to have more variation (Hu et al., 2010).

3.6 Verification process

Herein, to find whether the best combinations are applicable or not, they were examined for seven other typhoons (named in Sect. 2.3). The calculated values of RMSE, CC, MBE, and t for these typhoons confirms that the suggested combinations show the same results, which are given in Table 7.

3.7 Comparison with other studies for the wind speed prediction issue

In this part, two sets of simulations were defined according to the previous studies by Chandrasekar and Balaji (2012), and Angevine (2010), which were considered as the best physics options for wind prediction. The simulations are indicated by abbreviations of Sim 7, and Sim 8, respectively. The details of their represented physics options are indicated in Table 8.

These two suggested simulations for best wind predicting were conducted for typhoon Washi in 2011. The best wind-speed prediction by WRF model (simulation 4), CFSR data set, and these new simulations are compared (Fig. 8).

According to Fig. 8, the best physics options that were suggested for predicting typhoon intensity during this study (WRF) and also Sim 7 are nearly in the range of CFSR data set, and Sim 8 predicted stronger winds at some points.

4 Conclusions

From the results obtained, it is evident that there is no single combination of physics options that performs best for all desired parameters. However, the present study suggests suitable options for different variables, when considering typhoon existence in the South China Sea. According to different schemes defined in this paper, SST, LHF, SHF, precipitation rate, and wind speed are best estimated by simulations 6, 1, 5, 5, and 4, respectively. Therefore, the model configuration should be chosen from the viewpoint of the objective of the study being undertaken. The main conclusions of this study are as follows:

- This case study analysed the performance of different physics options available in the WRF model, for prediction of surface parameters under stormy conditions in the South China Sea.

Table 5. Statistical evaluation of different simulations for precipitation rate.

	Sim 1	Sim 2	Sim 3	Sim 4	Sim 5	Sim 6
RMSE	0.00027	0.00028	0.00026	0.00028	**0.00025**	0.00026
CC	0.329	0.105	0.264	0.369	**0.405**	0.301
MBE	0.00017	0.00017	0.00016	0.00018	**0.00015**	0.00016
t statistic	4.085	4.062	3.841	4.414	**3.699**	3.943

The best number for each statistical parameter is written in bold.

Table 6. Statistical evaluation of different simulations for wind speed.

	Sim 1	Sim 2	Sim 3	Sim 4	Sim 5	Sim 6
RMSE	4.28	3.87	4.10	**3.11**	4.39	3.15
CC	0.42	0.37	0.49	0.41	0.57	**0.70**
MBE	−2.69	−2.01	−2.93	**−1.64**	−3.09	−2.18
t statistic	4.13	**3.10**	5.20	**3.17**	5.07	4.91

The best number for each statistical parameter is written in bold.

Table 7. The values of statistic parameters for confirming the best combinations suggested for the selected parameters.

	RMSE	CC	MBE	*t* statistic
		SST		
Sim 1	0.62	0.85	−0.08	1.21
Sim 4	0.68	0.82	−0.13	1.8
Sim 5	0.63	0.84	−0.07	1.07
Sim 6	0.81	0.87	−0.06	0.66
		LHF		
Sim 1	129.49	0.82	−5.49	0.4
Sim 4	156.11	0.76	39.6	2.47
Sim 5	233.01	0.75	−127.39	6.16
Sim 6	137.84	0.81	−12.02	0.83
		SHF		
Sim 1	42.29	0.55	−17.43	4.27
Sim 4	24.65	0.47	−3.97	1.54
Sim 5	22.03	0.68	−2.87	1.24
Sim 6	31.97	0.67	−21.61	8.65
		Prate		
Sim 1	0.0014	0.68	0.00063	4.77
Sim 4	0.00142	0.72	0.00066	4.89
Sim 5	0.00135	0.73	0.00061	4.76
Sim 6	0.00141	0.67	0.00063	4.73
		Wind speed		
Sim 1	7.17	0.68	−1.57	2.13
Sim 4	6.9	0.72	1.24	1.73
Sim 5	7.79	0.63	−2.01	2.54
Sim 6	7.38	0.67	−1.95	2.6

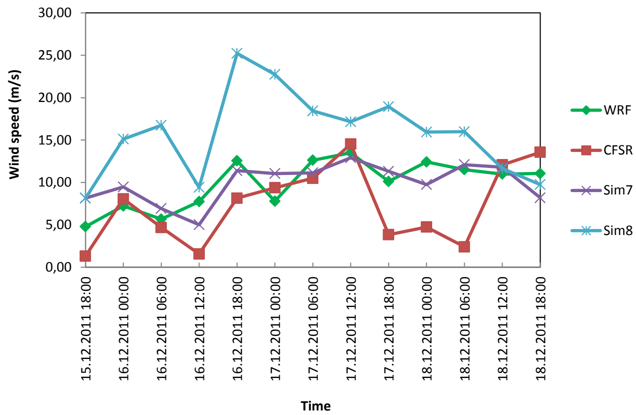

Figure 8. Comparison of wind-speed prediction for typhoon Washi through different simulations and data sets.

- The recommended combinations of physics options for the mentioned parameters were confirmed with seven other typhoons.
- Comparing the presented best simulations with the CFSR database showed that the suggested groups can be applicable in predicting issues except for precipitation rate.
- Overall, the performance of the WRF model is acceptable and satisfactory for prediction of important parameters related to typhoon intensity over the South China Sea region.
- Wind-speed prediction showed a reasonable result compared with other studies.

Table 8. Two simulations introduced by other studies.

	Sim 7	Sim 8
Microphysics	WRF single-moment 3-class	Eta
Longwave radiation	RRTM	RRTM
Shortwave radiation	RRTMG	Dudhia
Surface layer	MM5	TEMF
Land surface	Pleim Xiu	5-layer thermal diffusion
Planetary boundary layer	Mellor Yamada Janjic	TEMF
Cumulus parameterization	Grell-Devenyi	Kain Fritsch

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