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The efficiency of the WRF model for simulating typhoons

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Abstract

The Weather Research Forecast (WRF) model includes various configuration options related to physics parameters, which can affect the performance of the model. In this study, different 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 WRF model were exhaustively tested for typhoon Noul, which had 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 (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 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

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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). For example, Yang et al. (2011) studied wind speed and precipitation variations during typhoon Chanchu (2006), which occurred in the South China Sea. They carried out five different experiments using the PSU/NCAR 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.

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 suite 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 Weather Research Forecast (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, 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

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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 the 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 disturbance recorded 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 $\mathrm{km\,h^{-1}}$. 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 this day near Cambodia (JTWC, 2008).

2 Materials and methods

Final analysis six-hourly data sets (FNL) with a resolution of 1°, obtained from the National Centres for Environmental Prediction (NCEP), were inputted to the WRF model as initial and boundary conditions. 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 CFSR data by Saha et al. (2010), referred to as control data in this paper.

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. It should be noted that the SST-update function must be activated in the model configuration, in order to see SST variations during all simulations. The categories 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, 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-static (Jacovides and Kontoyiannis, 1995). These were used in this study for assessing model performance. These values were calculated for selected parameters, namely SSTs, latent heat flux (LHF), sensible heat flux (SHF), and precipitation rate in the center of 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

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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.

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 7 other typhoons, Peipah (2007), Tropical Depression 01W (2008), Kujira (2009), Chan-Hom (2009), Nangka (2009), Songda (2011), and Washi (2011). The aim was to confirm the scheme selection processes for each parameter. The typhoons were selected from all storm tracks dataset by Knapp et al. (2010).

3 Results and discussions

The data used for validation of the variables was derived from the CFSR dataset 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.

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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 temperature 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 six-hour period over the study duration. By and large, there is a general tendency towards over-prediction of SST when the typhoon is stronger, and under-prediction when the typhoon is weaker.

3.2 Latent heat flux

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

3.3 Sensible heat flux

As shown in Table 4, of the six simulations, number 4 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.

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3.4 Precipitation rate

In the case of precipitation rate, simulation 5 was the best-performing simulation, with consistently lowest RMSE, MBE, and t values, and 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 the control data. During the period of 14 to 17 November, the simulated data values for the typhoon were lower than the control data.

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. 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 same results which are given in the 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 sim7, and sim8, 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 (2011). The wind speed predicted by WRF model (best simulation), CFSR data set, and these new simulations are compared (Fig. 8).

According to the Fig. 8, the best suggested physics options for predicting typhoon intensity through this study (WRF) and also by other's studies (Sim 7 and Sim 8) are nearly in the range of CFSR data set. Of course the simulation 8 showed higher values in 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.

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

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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.	RRTM	Goddard	Pleim Xiu	Pleim Xiu	ACM2	Kain Fritsch
6	Lin et al.	RRTMG	RRTMG	TEMF	RUC	TEMF	Betts Miller Janjic

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Table 2. Statistical evaluation of different simulations for SST.

	Sim 1	Sim 2	Sim 3	Sim 4	Sim 5	Sim 6
RMSE	0.716	0.86	0.91	0.717	0.725	**0.65**
CC	−0.065	**0.31**	−0.1	0.156	−0.12	−0.16
MBE	0.11	−0.28	−0.25	−0.16	−0.10	**−0.016**
t statistic	0.38	0.84	0.7	0.57	0.35	**0.06**

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Table 3. Statistical evaluation of different simulations for LHF.

	Sim 1	Sim 2	Sim 3	Sim 4	Sim 5	Sim 6
RMSE	**95.758**	115.2	112.65	140.83	143.95	168.91
CC	**0.6901**	0.4987	0.6105	0.2132	0.514	0.5312
MBE	**−2.96**	13.39	−22.67	31.563	−49.65	−16.28
t statistic	**0.1577**	0.5967	1.0475	1.1727	1.8735	0.4938

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Table 4. Statistical evaluation of different simulations for SHF.

	Sim 1	Sim 2	Sim 3	Sim 4	Sim 5	Sim 6
RMSE	58.375	30.899	60.715	64.481	**23.694**	54.621
CC	0.6069	0.8885	0.7291	−0.029	**0.9337**	0.524
MBE	−12.85	−9.254	−22.38	−7.777	**0.483**	−14.384
t statistic	1.1505	1.6007	2.0224	1.7716	**0.0382**	1.392

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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	0.32941	0.10501	0.26422	0.36922	**0.40514**	0.30098
MBE	0.00017	0.00017	0.00016	0.00018	**0.00015**	0.00016
t statistic	4.08518	4.06251	3.84105	4.41405	**3.69970**	3.94333

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

	Sim 1	Sim 2	Sim 3	Sim 4	Sim 5	Sim 6
RMSE	4.283	3.873	4.104	**3.110**	4.390	3.151
CC	0.427	0.372	0.496	0.415	0.574	**0.709**
MBE	−2.697	−2.013	−2.932	**−1.643**	−3.097	−2.187
t statistic	4.133	**3.103**	5.205	**3.172**	5.075	4.916

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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

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Table 8. Two simulations introduced by other studies.

	Sim7	Sim8
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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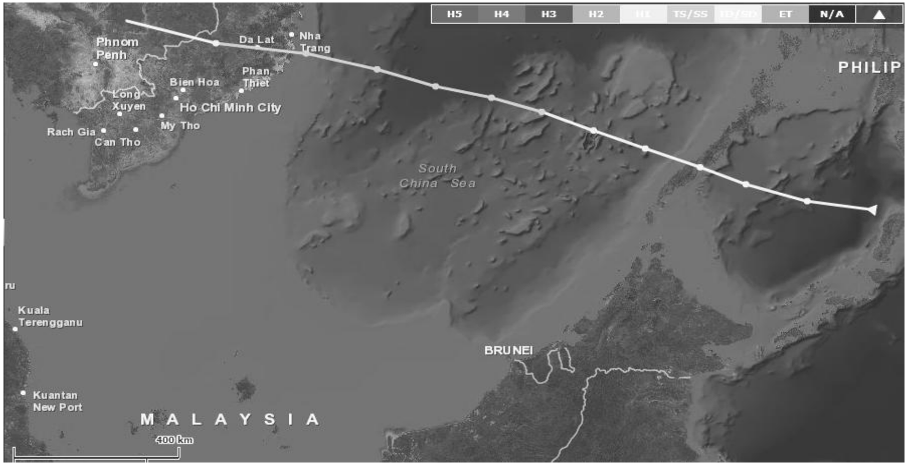

Fig. 1. Typhoon Noul trace in November (NOAA, 2008).

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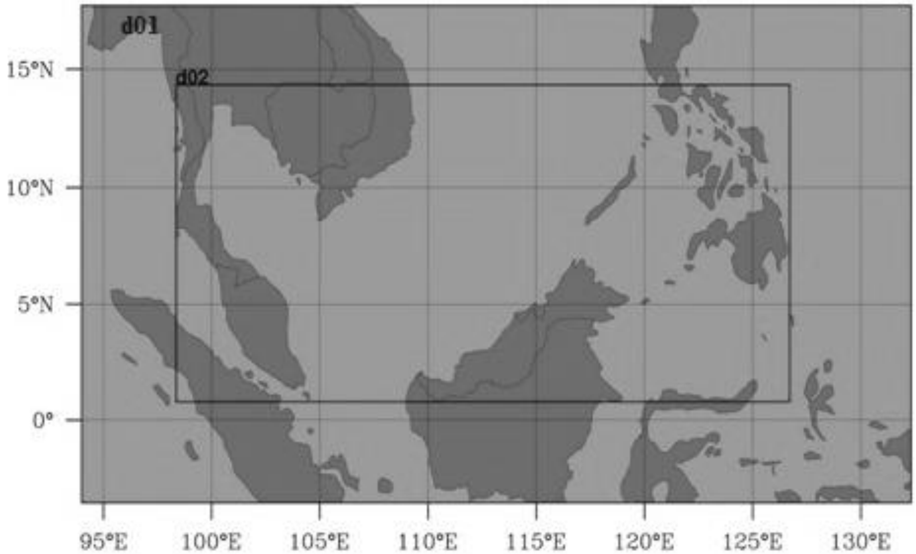

Fig. 2. Model domains.

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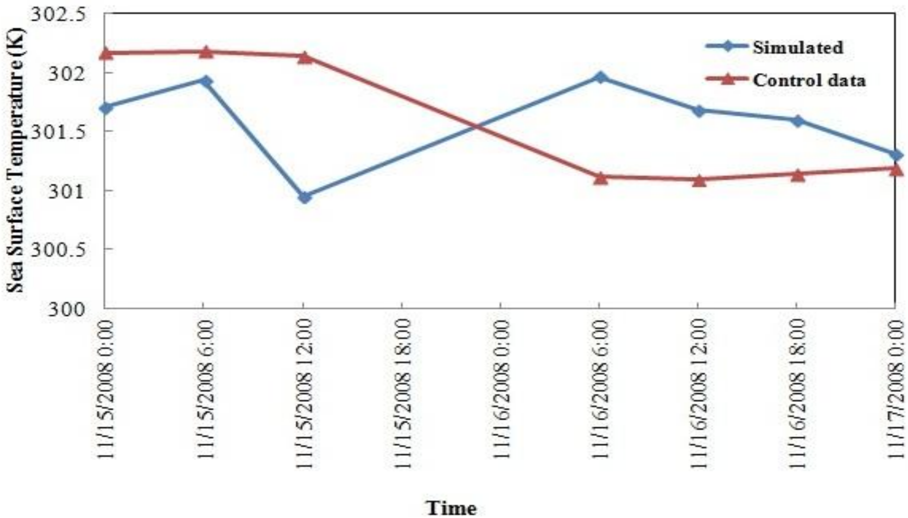

Fig. 3. Comparison of best model performance (simulation 6) with control data, for six-hourly SST prediction during Typhoon Noul.

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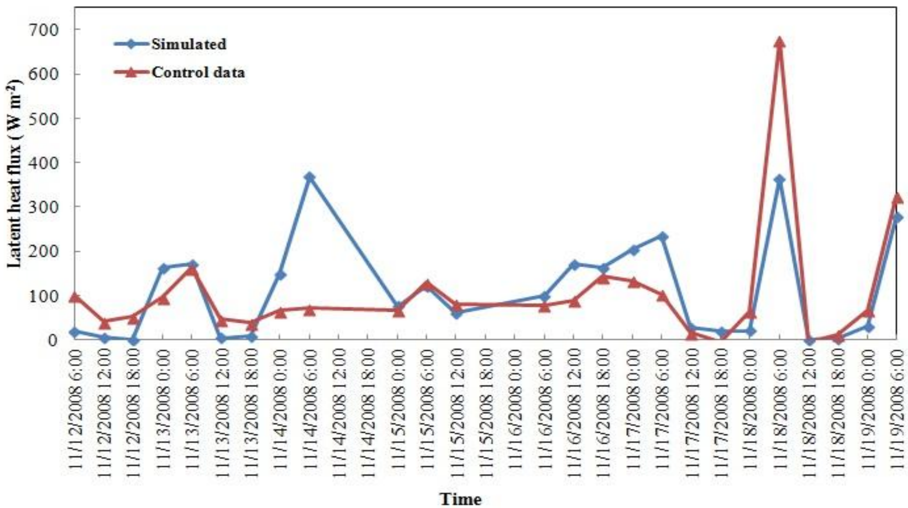

Fig. 4. Comparison of best model performance (simulation 1) with control data, for six-hourly LHF prediction during Typhoon Noul.

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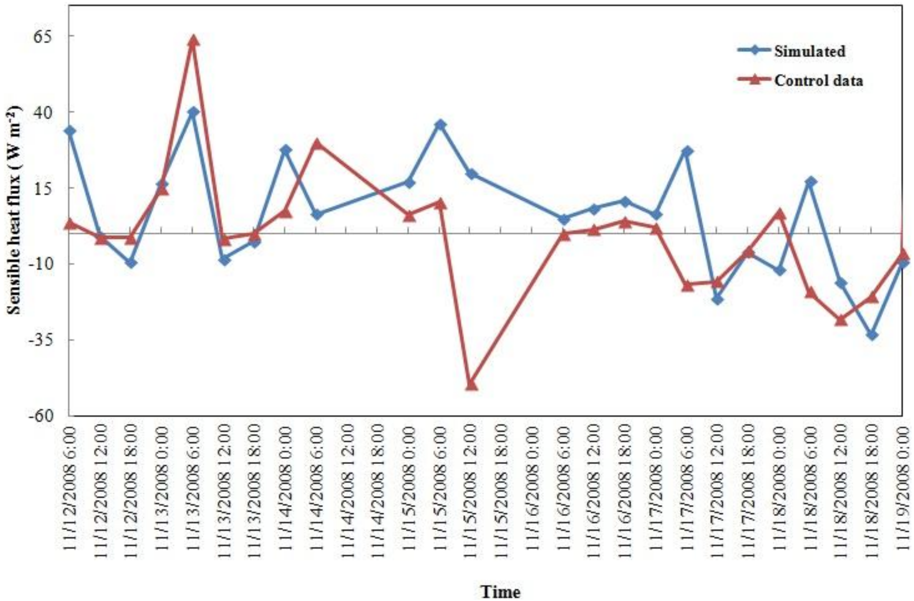

Fig. 5. Comparison of best model performance (simulation 5) with control data, for six-hourly SHF prediction during Typhoon Noul.

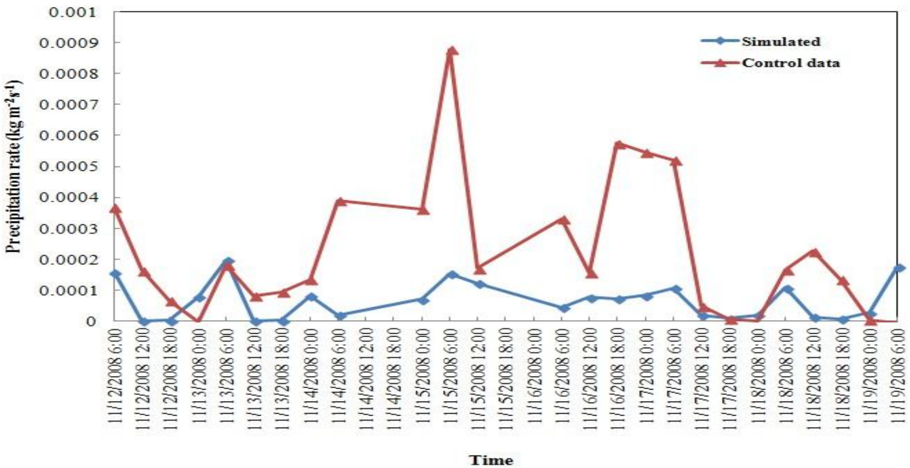

Fig. 6. Comparison of best model performance (simulation 5) with control data, for six-hourly precipitation rate prediction during typhoon Noul.

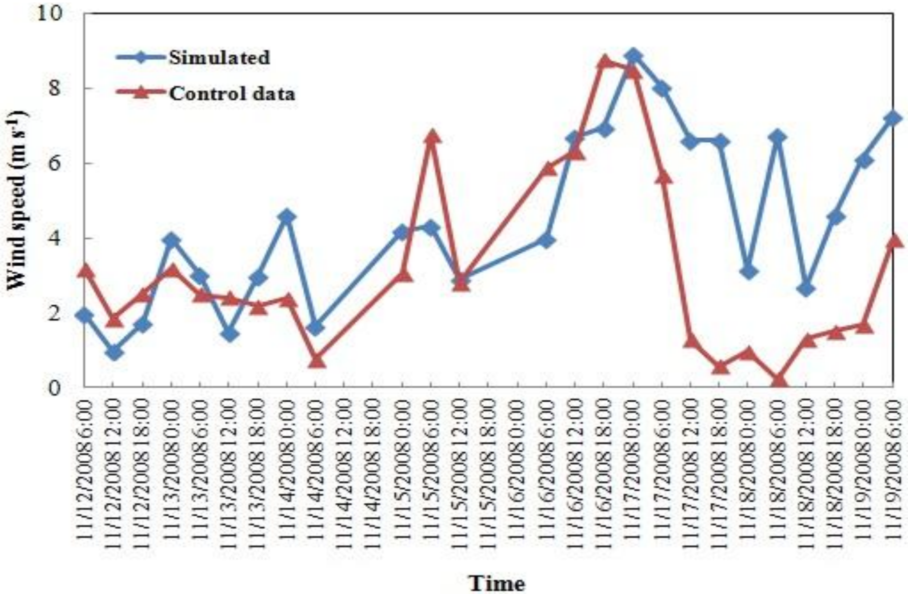

Fig. 7. Comparison of best model performance (simulation 4) with control data, for six-hourly wind prediction during Typhoon Noul.

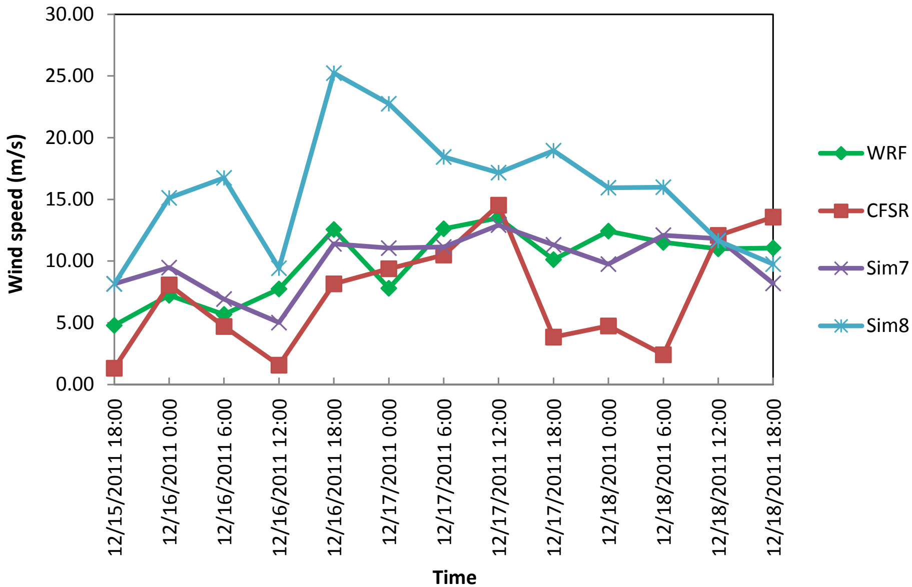

Fig. 8. Comparison wind speed prediction for typhoon Washi by different simulations and data sets.

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