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Performance of Different Parameterization Configurations of WRF-ARW Model during Heavy Rainfall over Mi Oya River Basin

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Abstract: Short-term intense precipitation is one of the hallmarks of climate change. Mi Oya River basin experiences severe seasonal floods annually, but the damage can be lessened by developing a numerical weather forecasting (NWF) model for the entire basin and incorporating it with effective reservoir management. Several areas in Sri Lanka have undergone NWF studies, however they are insufficient to determine the best physics schemes for the basin. This study investigates the Weather Research and Forecasting (WRF-ARW) model's predictability with varying three microphysics and two cumulus schemes to discover the optimal set of physics parameters for predicting heavy rainfall occurrences throughout the Southwest and Northeast monsoon seasons within a nested domain configuration. The WRF model's forecasting results at 3 km grid resolution were compared with four rainfall gauging stations in the basin for three rainfall events in May 2016, April 2018, and November 2015. Total Model Performance was derived for the evaluation utilizing bias, MAE, RMSE, Correlation Coefficient, and slope of each model's output data with observed rainfall data. After comparing the model output to data, WSM6 microphysics and Betts-Miller-Janjic cumulus with other default physics settings were determined to be the optimal physics combination to forecast weather across the region.

Keywords: Numerical weather forecasting (NWF), WRF-ARW, Mi Oya River basin, Physics schemes

1. Introduction

Weather forecasting is the science of predicting the weather through the use of physical principles and a variety of statistical and empirical methodologies. In addition to predicting atmospheric phenomena, weather forecasting also involves predicting surface changes produced by atmospheric circumstances such as snow and ice cover, storm tides, and flooding [1]. Numerical weather prediction (NWP) is a method for forecasting the weather using governing equations to represent the flow of fluids. These equations are transformed into parameterizations of various physical processes and coupled with initial and boundary conditions to simulate over a geographic area [2]. Today, these models are utilized extensively by weather forecasting services. Global models and mesoscale models with horizontal resolutions in the range of a few kilometers to a few tens of kilometers are among the most frequently considered models. Recent research has focused on the performance of NWP models with even higher spatial resolutions in order to provide location-specific forecasts. The topic of selecting the optimal initial circumstances for numerical weather prediction (NWP) is of enormous practical significance and has been studied by researchers from various disciplines [3]. These research often provide seemingly contradictory findings, but their links become apparent upon closer investigation. According to local and international research, the Weather Research Forecasting (WRF) model was adopted by the majority of researchers when compared to other accessible forecasting models such as RegCM3, DMI-HIRHAM, CNRM-ARPEGE, UQAM-CRCM5 and MPI-REMO. This model has yielded results that are better than those of previous numerical forecasting models [4]. However, there is currently no definitive conclusion regarding physics systems in Sri Lanka, necessitating additional research.

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Hopefully, this study will address this research vacuum with reasonable content.

The Weather Research Forecasting Model (WRF) is a community-based, open-source model. WRF delivers operational forecasting on a platform that is both flexible and computationally efficient, reflecting current improvements in physics, numeric, and data assimilation offered by developers from a large research community [5, 6, 7]. As a result, the WRF model was chosen for this investigation to predict the weather in the region. Microphysics and cumulus parameterization schemes are this model's most critical physical schemes for capturing heavy precipitation [8].

Due to the intense weather conditions during the monsoon seasons, seasonal flooding severely affects the Mi Oya River basin annually [9]. During these intense downpours, the overflowing of the Thabbowa and Iginimitiya reservoirs causes extensive flooding downstream of the reservoirs. By developing a rainfall forecasting model for the entire river basin and incorporating it with efficient reservoir operation, it is possible to limit flood damages significantly.

Mi Oya is a 118 km long river in Sri Lanka's northwestern region. It begins at Saliyagama and travels northwest to Puttalam, where it empties into the Indian Ocean. Mi Oya river basin has a catchment area of 1530 km^2. The annual precipitation volume and sea discharge volume are 1000 mm and 412 million m^3, respectively [10, 11]. The Mi Oya River Basin is highly impacted by seasonal flooding each year due to the intense weather conditions. In our study, we hope to develop physics models that are appropriate for considering two significant rainfall events that happened in the Mi Oya basin.

2. Literature Review

2.1 Weather Research and Forecast Model (WRF)

Global Climate Models (GCMs) typically resolve sub-grid-scale characteristics at coarser spatial resolutions (1^{o}x1^o). Hence downscaling is necessitated for investigations on regional and local effects [12, 13]. The two main categories of downscaling methods are dynamical and statistical. Dynamic downscaling is the technique of dynamically extrapolating the impacts of large-scale climate processes to relevant regional or local scales using high-resolution regional simulations [14, 15, 16]. A range of statistical techniques are applied to statistical downscaling to establish the connections between observable local climate patterns and the large-scale climate patterns indicated by global climate models. These connections are used in conjunction with GCM outputs to convert climate model outputs into statistically enhanced products, which are frequently deemed more suitable for use as input in regional or local climate impacts studies [17, 18].

The WRF is a numerical weather prediction and atmospheric system developed for both operational and research purposes [19, 20]. It is a supported "community model" created using the freely available resource with decentralized development and centralized support. The Advanced Research WRF (ARW) and Nonhydrostatic Mesoscale Model (NMM) are WRF's two dynamical cores. The WRF model development was led by among National Center for Atmospheric Research's (NCAR), Mesoscale and Microscale Meteorology (MMM) Division, National Oceanic and Atmospheric Administration's (NOAA), National Center for Environmental Prediction (NCEP), Earth System Research Laboratory (ESRL), Department of Defense's Air Force Weather Agency (AFWA), Naval Research Laboratory (NRL), the Center for Analysis and Prediction of Storms (CAPS) at the University of Oklahoma, and the Federal Aviation Administration (FAA) with the participation of university scientists [9, 21]. The WRF-ARW is extensively used in chemistry applications, global simulations, and idealized simulations at various resolutions [22]. Examples of applications include regional climate studies, data assimilation studies, and real-time (operational) forecasting [22, 23].

2.2 Status of WRF Models in Sri Lanka

Rodrigo et al. [24] conducted a sensitivity study of WRF numerical modelling for predicting heavy rainfall in Sri Lanka in 2018. In this investigation, two high rainfall events that were observed across Sri Lanka were simulated using the WRF-ARW model. This study uses four different microphysics schemes (WDM5, WDM6, WSM5 and WSM6) and nine cumulus parameterizations (KF, Old Simplified Arakawa-Schubert, BMJ, GF, MKF, Grell-3, Tiedtke, New Tiedtke and New Simplified Arakawa-Schubert) were used. Although the spatial distribution of rainfall could be simulated similar to observed rainfall from the gauging stations, results of their model did not accurately estimate the amount of precipitation. The model configurations with WSM6 and BMJ schemes employed in both the coarse and fine domains, as well as without the cumulus (BMJ) in the tested fine domain, had the best overall performances throughout the southwest monsoon season. Model combinations utilizing WSM6 with BMJ schemes and WDM6 with MKF schemes only in the coarse domain and no cumulus scheme exhibited the best overall performance during the northeast monsoon season.

Darshika et al. (2014) simulated the excessive rainfall event that was recorded in Sri Lanka from December 19 to December 28 of 2014 using WRF-ARW (version 3.0.1), two cumulus parameterization schemes (KF and BMJ), as well as three microphysics schemes (Kessler, WSM5, and WSM6) [25]. The results revealed that, with the exception of the north of Sri Lanka on December 25, every trial significantly underestimated the amount of precipitation and relatively widespread heavy rainfall that occurred across much of the island.

Numerous scientific researches on weather forecasting have been conducted in Sri Lanka [22, 26, 27, 28]. However, there is still no precise conclusion on physics schemes from the Sri Lankan studies, which calls for further research. We anticipate this study will address that research gap with a reasonable amount of information.

2.3 Physics Schemes

Physics parameterizations approximate the bulk effects of physical processes that are too complex or poorly understood to be expressed explicitly [29]. Microphysics of clouds and precipitation, radiation transported through the atmosphere, planetary boundary layer and surface layer, turbulence and diffusion, and cumulus convection are parameterizations of the WRF Model.

The WRF model offers multiple microphysics options, including the Kessler scheme [30], Lin et al. scheme [31], WSM3 scheme (WRF Single Moment 3 class scheme) [32], WSM5 scheme (WRF Single Moment 5 class scheme) [32], WSM6 scheme (WRF Single Moment 6 class scheme) [32], and the Ferrier scheme [33]. The Kessler scheme was evolved from the COMMAS (Collaborative Model for Multi-scale Atmospheric Simulation) model, which is a simple warm cloud scheme consisting of water vapour, cloud water, and rain [30, 34]. The Lin et al. method [31] classifies hydrometeors into six categories: water vapour, cloud water, precipitation, cloud ice, snow, and graupel. The WSM3 method estimates three types of hydrometeors: vapour, cloud water/ice, and precipitation/snow, and is sometimes referred to as a simple ice scheme [31]. The WSM5 method is similar to the WSM3 ice scheme, but vapour, precipitation, snow, cloud ice, and cloud water are stored in five distinct arrays [32]. WSM6 scheme is a six-class scheme that extends WSM5 scheme to incorporate graupel and its accompanying processes [32, 35]. The Ferrier scheme forecasts changes in water vapour and condensate as cloud water, precipitation, cloud ice, and precipitation ice (snow/graupel/sleet) [33].

Cumulus convection significantly influences the behaviour of weather and climate systems on a global scale. The physical processes related with cumulus convection occur on scales that weather and climate prediction models cannot resolve. The WRF model has numerous cumulus scheme alternatives, including Kain-Fritsch (KF) [36], Betts-Miller-Janjic (BMJ) [37], Grell-Devenyi Ensemble (GD) [38], and Multiscale Kain–Fritsch Scheme (MKF) [39]. In the WRF model, the cumulus parameterization scheme is one of the physics options that consider cloud convection when predicting the weather. Cumulus schemes are primarily concerned with forecasting convective precipitation [22, 40, 41]. The KF scheme is a mass flux parameterization scheme that can be explained by small-scale processes of convection [36]. Deep and shallow convection are both included in the BMJ convective adjustment scheme [37]. Multiple cumulus schemes are included in the GD scheme, which are all mass-flux schemes with different updraft and downdraft entrainment and detrainment parameters and precipitation efficiencies [38]. MKF scheme is an updated version of the KF scheme that takes into account subgrid-scale cloud radiation interactions, a dynamic adjustment time scale, the effects of subgrid-scale cloud updraft mass fluxes on grid-scale vertical velocity and an entrainment methodology [39].

3. Methodology

In this work, the used weather forecasting model is Advanced Research WRF (ARW) version 4.0, produced by the National Center for Atmospheric Research (NCAR). The WRF-ARW modelling system is intended to be a flexible, state-of-the-art simulation system for the atmosphere that is portable and efficient on existing parallel computing systems. The ARW applies to a wide variety of applications at sizes ranging from metres to thousands of kilometres, such as idealized simulations, parameterization research, real-time NWP, data assimilation, earth system model coupling, model training, and educational support, etc. This study seeks to identify an appropriate physical combination for the parameterization of the Mi Oya River basin.

Microphysics and cumulus physics are the most sensitive in numerical weather prediction over tropical regions [22]. Before operational use, the model output must be examined for several microphysics and cumulus physics parameters in order to determine the optimal physics parameters [42]. Initially, the literature on WRF studies conducted for Sri Lanka and other tropical countries were examined for physics schemes with better performance. Then, six physics combinations were selected for the model study, as shown below, indicating the chosen microphysics and cumulus schemes.

- Comb. 1 Kessler-Kain Fetish
- Comb. 2 Kessler-Betts Miller Janjic
- Comb. 3 WSM3-Kain Fetish
- Comb. 4 WSM6-Betts Miller Janjic
- Comb. 5 WSM3-Betts Miller Janjic
- Comb. 6 WSM6-Kain Fetish

The remaining schemes are default schemes of the WRF model, which were not changed within the selected combinations. The used default schemes are Yonsei University planetary boundary layer scheme (YSU) [43], RRTM longwave radiation scheme [44], Dudhia shortwave radiation scheme [45], Unified Noah land surface scheme [46], and Revised MM5 surface layer scheme [47]. A higher spatial resolution can improve the quality of model performance, but it typically requires more time to complete model simulations and generates results that need more powerful computer resources for the simulations, hence increasing the computing cost. Therefore, nesting was used to achieve a satisfactory balance between accuracy and computation cost. In this study, each integration was executed utilizing a domain with one-way nesting. The selected outer, middle, and inner domains have dimensions of 1782 km x 1782 km, 594 km x 594 km, and 189 km x 189 km, respectively, with resolutions of 27 km, 9 km, and 3 km, respectively. The domains share the same center (i.e. Mee Oya city) and inner domain covers the entire basin (see Figure 1).

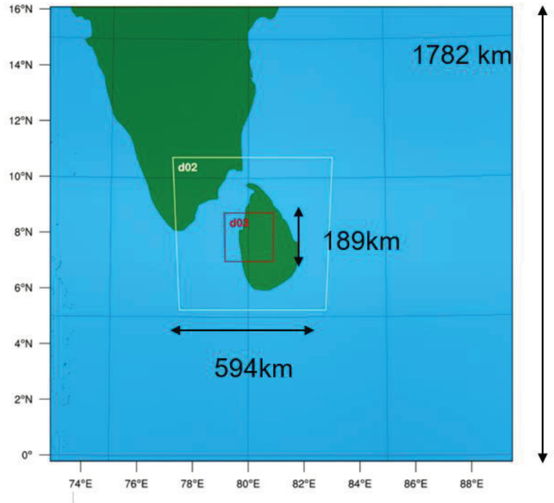

Figure 1 - WRF Domain Configuration

Initial and lateral boundaries were obtained from National Center for Atmospheric Research (NCAR). Among the available multiple datasets, data from NCEP FNL (Final) operational global analysis and forecast data with a resolution of 0.25-degree by 0.25-degree were utilised every six hours [48]. The FNL data has more accuracy as it incorporates more observational data through Global Data Assimilation System (GDAS).

Initially, the best physics configuration for the Mi Oya River basin was identified for a southwest monsoon event from May 13 to May 16, 2016. The model was then tested with a second instance of a southwest monsoon from April 10 to April 16, 2018. The model was then assessed for a northeast monsoon using the rainfall event from November 11 to November 16, 2015. The spin-up period for all events was 24 hours before the rainfall event.

For this domain, observed daily rainfall data for the selected rainfall events from rainfall gauging stations of the Iginimitiya (7°55'48.00"N, 80°7'48.00"E), Tabbowa (8°4'12.00"N, 79°57'0.00"E), Puttalam (8°1'48.00"N, 79°49'48.00"E) and Atharagalla (7°55'12.00"N, 80°16'48.00"E) stations (Figure 2) were collected from the meteorological Department of Sri Lanka. For each physics combination, the model's predicted daily cumulative rainfall for the 3 km domain was compared to observed data.

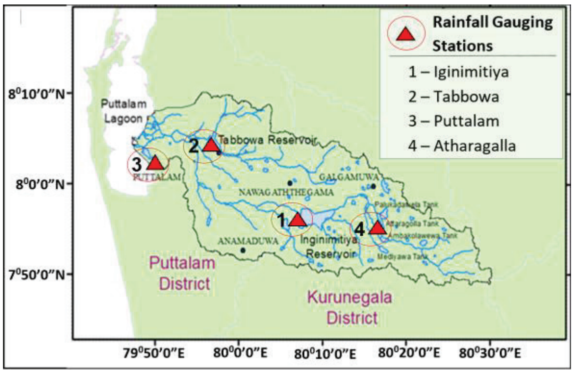

Figure 2 - Mi Oya River Basin and Selected Rainfall Stations

Model performances under various parameterization combinations were determined using bias, Mean Absolute Error (MAE), Root Mean Square Root Error (RMSE), Correlation Coefficient (Corr.), and slope (Slope) at each recorded rainfall station. To determine the overall performance of the model, several indicators must be aggregated. As the bias (BIAS), MAE, and RMSE have units, they cannot be added to the correlation and slope immediately. By dividing the bias, MAE, and RMSE by their respective observations, it is possible to convert parameters to dimensionless values. The average can then be computed by adding |1-corr.| and |1-slope| together. This is referred to as Total Model Performance (TMP) as given in Eq.1 where, Y_o (mean) is the mean of the observations. A zero TMP value indicates that the model output value is close to the observations, whereas 1 indicates that the model output value is far from the observations.

$$TMP = \frac{\frac{MAE+RMSE+BIAS}{Y_0(mean)} + (1-Corr.) + |1-Slope|}{5} \quad \dots (1)$$

The identified optimum physics scheme was then used to evaluate the forecasting capabilities of the model for 24 hours. The rainfall was forecasted for 24 hours from boundary conditions available on May 14, 2016. Forecasted precipitation for May 15, 2016 was then compared to the observed precipitation on May 15, 2016.

4. Results and Discussion

The daily rainfall accumulation data for the Mi Oya River basin was produced using simulations of the WRF-ARW model. The optimal physics scheme out of six combinations was identified based on three precipitation events.

4.1 Identification of Optimum Physics Schemes (Southern West Monsoon Event in May 2016)

Figure 3 shows the variation of daily precipitation of model combinations in comparison to average of observation stations. During the 15th and 16th of May 2016, observations showed rainfall totals of 100 mm and 150 mm, respectively. All the models overestimated these precipitations.

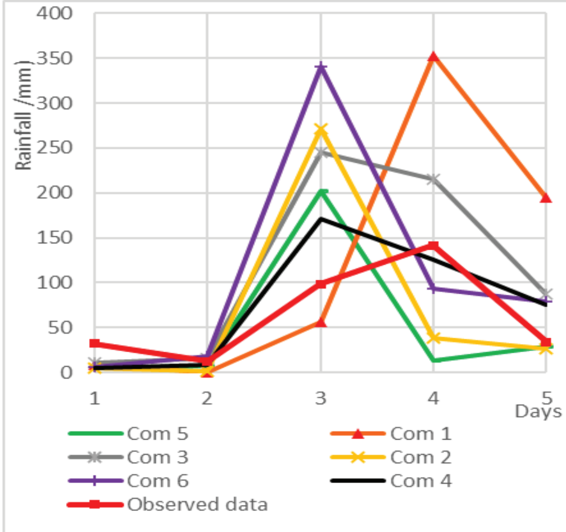

Figure 3 – Daily Rainfall of the Model Combination vs Average of Observations for the Period of 13 to 17 May 2016

A Taylor diagram was utilized to visualise the model's performance as shown in Figure 4. The highest correlation has been shown by combinations 1, 3, and 4. However, combination 4 showed the lowest variance and a reasonable correlation value out of those three potential outcomes.

The statistical comparison of the predicted and observed precipitation for 2016 May precipitation event is shown in Table 1 considering the Total Model Performances (TMP) with bias, RMSE, slope, and MAE. The findings show that combination 4 (WSM6 microphysics parameter and Betts Miller Janjic cumulus parameter) has the lowest TMP value (0.57) and good Pearson correlation (0.60). This suggests that combination 4 is the most accurate combination for forecasting this rainfall event. The second-best combination is combination 3, and the worst is combination 1.

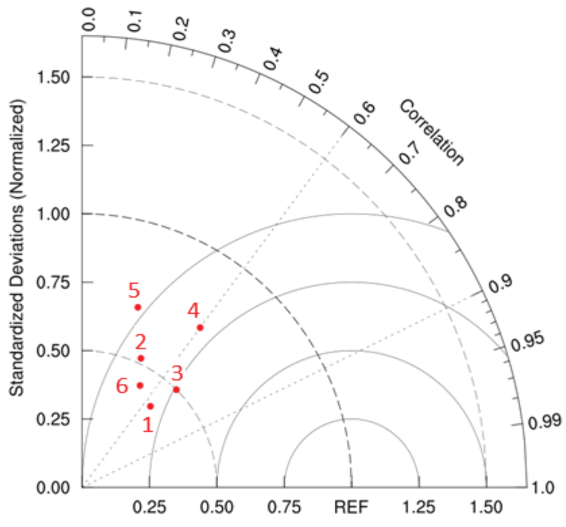

Figure 4 - Taylor Diagram for Displaying Standardized Deviation and Correlation for May 2016 Rainfall Event

Table 1 - Statistical Comparison between Model Output Data vs Observed Data for May 2016 Rainfall Event

Combination	BIAS	MAE	RMSE	Slope	Correlation	TMP
1	59	92	128	0.25	0.65	1.09
2	4	67	96	0.21	0.42	0.79
3	51	67	96	0.34	0.69	0.88
4	13	44	63	0.41	0.60	0.57
5	-12	54	82	0.21	0.30	0.69
6	43	76	118	0.21	0.50	1.00

4.2 Verification

4.2.1 Verification for Southern West Monsoon in April 2018

As mentioned in the methodology, model verification was carried out from 10 to 16 April 2018. Performance of all the combinations in comparison to average observations are shown in Figure 5. Combinations 4, 5 and 6 could capture the peak though combinations 1 and 3 underestimated the peak and got unrealistic rainfall on the day before and the next day. Taylor diagram shown in Figure 6 illustrates the comparison between model output data and observed data of the six simulated physics combinations, combination 4 (WSM6 microphysics parameter and Betts Miller Janjic cumulus parameter) has the highest correlation value and the lowest variance with the observed dataset.

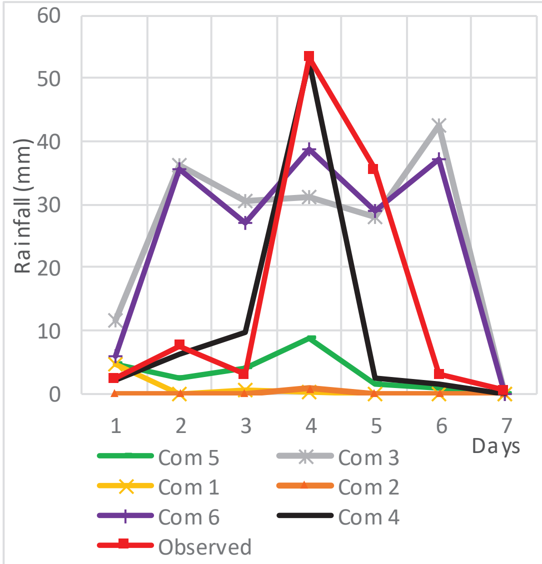

Figure 5 - Daily Rainfall of the Model Combinations vs Average Observations for the Period of 10 to 16 April 2018

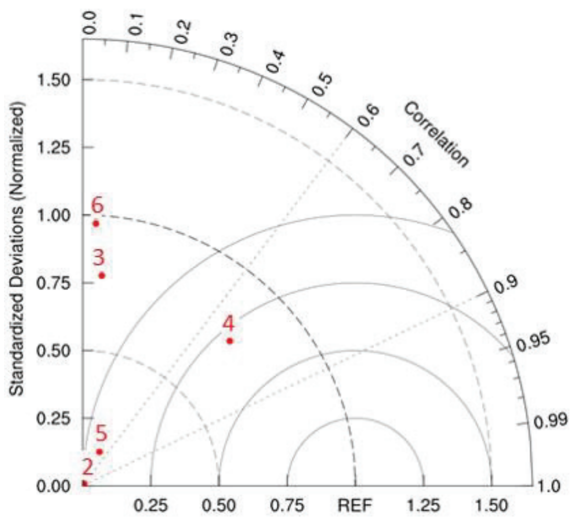

Figure 6 - Taylor Diagram for Displaying Standardized Deviation and Correlation for the Event of April 2018

For each physics combination, a statistical comparison of the model output data with the observed data was made, as shown in Table 2. The physics combination 4 (WSM6 microphysics parameter and Betts Miller Janjic cumulus parameter) exhibited a much better relation to the observed data than other selected physics combinations, taking into account the best correlation value (0.71) and TMP value (0.39). This verifies that combination four performs better than the rest.

Table 2 - Statistical Comparison between Model Output Data vs Observed Data for April 2018 Rainfall Event

Combination	BIAS	MAE	RMSE	Slope	Correlation	TMP
1	-14	15	29	-1.30	-0.12	1.09
2	-15	15	29	35.24	0.54	7.33
3	11	26	33	0.12	0.09	1.56
4	-4	10	18	0.93	0.71	0.39
5	-12	14	27	3.18	0.44	0.94
6	10	26	36	0.05	0.05	1.33

4.2.2 Verification for Northeast Monsoon in November 2015

Since the physics combination 4 (WSM6 for microphysics scheme and Betts Miller Janjic cumulus parameter) has performed better based on above two rainfall events during the southwest monsoonal season, the study was carried out further to clarify the model performance during northeast monsoonal season due to atmospheric changes in different monsoonal seasons. Figure 7 shows the cumulative daily rainfall of the average observations stations vs the model combinations from 11 to 16 November 2015. Though several combinations show higher precipitation amount on 15th November 2015, only few combinations capture the fluctuation of precipitation.

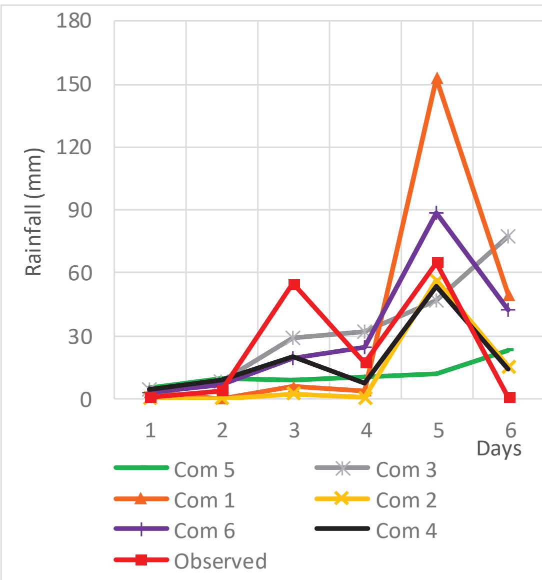

Figure 7 - Daily Rainfall of the Model Combinations vs Average Observations for the Period of 11 to 16 November 2015

Taylor diagram in Figure 8 provides clear illustration on the accuracy of the combinations. Combinations 2 and 4 have higher correlations, while the remaining combinations have lower correlations.

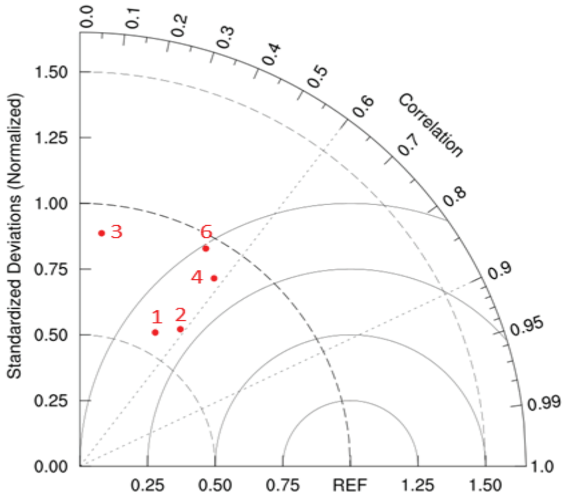

Figure 8 - Taylor Diagram Displaying Standardized Deviation and Correlation for the Event of November 2015

The statistical comparison among these combinations is shown in Table 3. Combination 4 (WSM6 microphysics parameter and Betts Miller Janjic cumulus parameter) also performs better in the northeast, according to the results considering TMP. This leads us to the conclusion that combination 4 is suitable for both seasons.

Table 3 - Statistical Comparison between Model Output Data vs Observed Data for November 2015 Rainfall Event

Combination	BIAS	MAE	RMSE	Slope	Correlation	TMP
1	12	34	66	0.28	0.48	1.19
2	-11	17	62	0.90	0.58	0.66
3	3	27	50	0.10	0.09	1.03
4	-6	16	30	0.78	0.57	0.47
5	-12	24	67	-0.06	-0.09	1.09
6	7	21	38	0.40	0.49	0.77

4.3 Capabilities of Weather Forecasting

Final simulation was carried out in order to evaluate the accuracy of the forecast with 24 hour lead time. Figure 9 compares forecasted results with observed and model output data for 15 May 2016 rainfall event. According to observations, two stations (i.e. Puttalam and Atharagalla) recorded precipitation more than 100 mm per day and other two stations recorded precipitation close to 90 mm/day. Model forecasted a maximum of 49 mm/day for Puttalam though the model could not capture the high precipitation amount. Further studies are required to analyse model capabilities for forecasting longer durations.

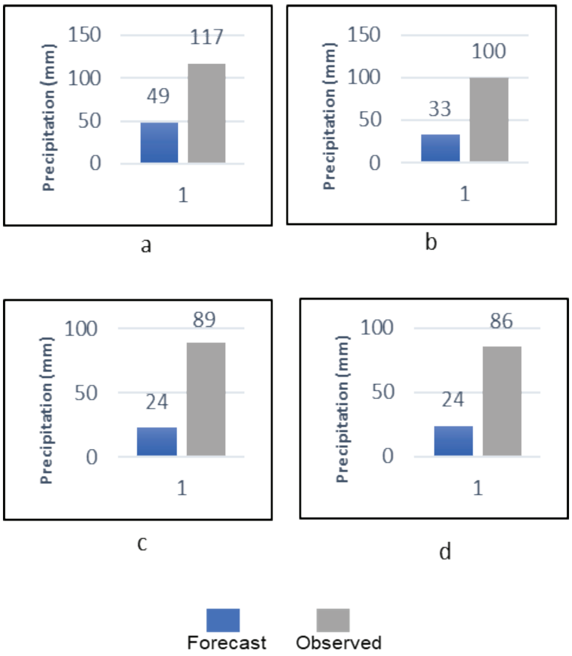

Figure 9 - Forecasted Results with Observed and Model Output Data on 15/05/2016 for Each Gauging Station a) Puttalam b) Athragalla c) Thabbowa d) Iginimitiya

5. Conclusions

- During the May 2016 rainfall event, the best physics combination was found to be between the WSM6 microphysics and Betts-Miller-Janjic cumulus schemes (Combination 4), yielding a Correlation Coefficient and TMP of 0.60 and 0.57, respectively.
- Combination 4 performed best during the verification simulations for the southwest and northeast monsoons, with correlation coefficients of 0.71 and TMPs of 0.39 for the event in April 2018 and 0.57 and 0.47 for the rainfall event in November 2015, respectively.
- According to this study's findings of the tested six physics combinations, the WSM6 microphysics and Betts-Miller-Janjic cumulus options with default parameters for other options produced the best rainfall prediction over the Mi Oya River basin, Sri Lanka.
- It should be noted that these findings only pertain to the WRF model's default schemes, except from tested microphysics and cumulus schemes; thus, studies are warranted to achieve more accurate predictions with the consideration of other physics scheme parameters with WSM6 microphysics and Betts-Miller-Janjic cumulus schemes, as well as more rainfall events over the Mi Oya River basin, Sri Lanka.

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References

1. Doblas-Reyes, F. J., Garcia-Serrano, J., Lienert, F., Biescas, A. P. and Rodrigues, L. R., “Seasonal Climate Predictability and Forecasting: Status and Prospects”, *Wiley Interdisciplinary Reviews: Climate Change*, Vol. 4, No. 4, July, 2013, pp. 245-268.

2. Kaufmann, P., Schubiger, F. and Binder, P., “Precipitation Forecasting by a Mesoscale Numerical Weather Prediction (NWP) model: eight years of experience”, *Hydrology and Earth System Sciences*, Vol. 7, No.6, December, 2003, pp. 812-832.

3. Sandu, I., Beljaars, A., Bechtold, P., Mauritsen, T. and Balsamo, G., "Why is it so difficult to Represent Stably Stratified Conditions in Numerical Weather Prediction (NWP) Models?", *Journal of Advances in Modeling Earth Systems*, Vol. 5, No. 2, June, 2013, pp. 117-133.

4. Buzzi, A., Davolio, S., Malguzzi, P., Drofa, O. and Mastrangelo, D., "Heavy Rainfall Episodes over Liguria in Autumn 2011: Numerical Forecasting Experiments", *Natural Hazards and Earth System Sciences*, Vol. 14, No. 5, May, 2014, pp. 1325-1340.

5. Done, J., Davis, C. A. and Weisman, M., "The Next Generation of NWP: Explicit Forecasts of Convection using the Weather Research and Forecasting (WRF) model", *Atmospheric Science Letters*, Vol. 5, No. 6, July, 2004, pp. 110-117.

6. Carvalho, D., Rocha, A., Gomez-Gesteira, M. and Santos, C., "A Sensitivity Study of the WRF Model in Wind Simulation for an Area of High Wind Energy", *Environmental Modelling & Software*, July, 2012. Vol. 33, pp. 23-34.

7. Mohan, M. and Sati, A. P., "WRF Model Performance Analysis for a Suite of Simulation Design", *Atmospheric Research*, Vol. 169, 2016, pp. 280-291.

8. Chawla, I., Osuri, K. K., Mujumdar, P. P. and Niyogi, D., "Assessment of the Weather Research and Forecasting (WRF) Model for Simulation of Extreme Rainfall Events in the upper Ganga Basin", *Hydrology and Earth System Sciences*, Vol. 22, No. 2, 2018, pp. 1095-1117.

9. Bandaranayake, G. M. and Kumara, S., "Modeling for River Basin Management: Its Application to Mi Oya in the Dry Zone of Sri Lanka", *Proceedings of the Fifth International Research Conference On Humanities and Social Sciences (IRCHSS) 2016*, 2016.

10. De Silva, S. S., "Reservoirs in Sri Lanka and their Fisheries", *FAO Fisheries technical paper,* 1988, pp. 128.

11. Madumali, G. V. H. M and Manamperi, M. M. S. B., "Impact of Water Scarcity on Agriculture in Mi Oya River Basin", *Journal of Archaeology, Tourism & Anthropology, Department of Archaeology, University of Kelaniya*, Vol. I, No. II, 2020, pp. 80-89.

12. Wang, Y., Jiang, J., Zhang, J., He, J., Zhang, H., Chi, X. and Yue, T., "An Efficient Parallel Algorithm for the Coupling of Global Climate Models and Regional Climate Models on a Large-Scale Multi-Core Cluster", *The Journal of Supercomputing*, Vol. 74, No. 8, August, 2018, pp. 3999-4018.

13. Moncrieff, M. W., Liu, C. and Bogenschutz, P., "Simulation, Modeling, and Dynamically Based Parameterization of Organized Tropical Convection for Global Climate Models", *Journal of the Atmospheric Sciences*, Vol. 74, No. 5, May, 2017, pp. 1363-1380.

14. Xue, Y., Janjic, Z., Dudhia, J., Vasic, R. and De Sales, F., "A Review on Regional Dynamical Downscaling in Intraseasonal to Seasonal Simulation/Prediction and Major Factors that Affect Downscaling Ability", *Atmospheric Research*, Vol. 147, October, 2014, pp. 68-85.

15. Xu, Z., Han, Y. and Yang, Z., "Dynamical Downscaling of Regional Climate: A Review of Methods and Limitations", *Science China Earth Sciences*, Vol. 62, No. 2, February, 2019, pp. 365-375.

16. Boe, J., Terray, L., Habets, F. and Martin, E., "Statistical and Dynamical Downscaling of the Seine Basin Climate for Hydro-Meteorological Studies", *International Journal of Climatology: A Journal of the Royal Meteorological Society*, Vol. 27, No. 12, October, 2007, pp. 1643-1655.

17. Lanzante, J. R., Dixon, K. W., Nath, M. J., Whitlock, C. E. and Adams-Smith, D., "Some Pitfalls in Statistical Downscaling of Future Climate", *Bulletin of the American Meteorological Society*, Vol.99, No.4, April, 2018, pp. 791-803.

18. Kazmi, D. H., Li, J., Rasul, G., Tong, J., Ali, G., Cheema, S. B., Liu, L., Gemmer, M. and Fischer, T., "Statistical Downscaling and Future Scenario Generation of Temperatures for Pakistan Region", *Theoretical and Applied Climatology*, Vol. 120, No. 1, April, 2015, pp. 341-350.

19. Mafas, M., Muhammadh, K. M., Weerakoon, S. B. and Mutua, F., "Comparative Study of WRF and REGCM Weather Predictions for the Upper Mahaweli River Basin", *In Proceedings of the 7th International Conference on Sustainable Built Environment, Kandy, Sri Lanka,* December, 2016, pp. 16-18.

20. Hu, X. M., Nielsen-Gammon, J. W. and Zhang, F., "Evaluation of Three Planetary Boundary Layer Schemes in the WRF Model", *Journal of Applied Meteorology and Climatology*, Vol. 49, No. 9, September, 2010, pp.1831-1844.

21. Wang, W. and Seaman, N. L., "A Comparison Study of Cnvective Parameterization Schemes in a Mesoscale Model", *Monthly Weather Review*, Vol. 125, No. 2, 1997, pp. 252-278.

22. Nandalal, K. D. W., Sachindra, D. A. and Ratnayake, U. R., "Application of WRF Weather Model to Forecast Precipitation in Nilwala River Basin", *Engineer: Journal of the Institution of Engineers, Sri Lanka*, 2012. 45(1), pp. 51-64.

23. Lo, J. C. F., Yang, Z. L. and Pielke Sr, R. A, "Assessment of three dynamical climate downscaling methods using the Weather Research and Forecasting (WRF) model", *Journal of Geophysical Research: Atmospheres*, Vol. 113, No. D9, 2008.

24. Rodrigo, C., Kim, S. and Jung, I. H., "Sensitivity Study of WRF Numerical Modeling for Forecasting Heavy Rainfall in Sri Lanka", *Atmosphere*, Vol. 9, No. 10, September, 2018, pp. 378.

25. Darshika, D. W. T. T. and Premalal, K. H. M. S., "Simulate Heavy Rainfall during 19th to 28th December 2014 using WRF for different atmospheric physics", *Department of Meteorology*, 2014, pp. 32-40.

26. De Silva, G. T., Herath, S., Weerakoon, S. B. and Rathnayake, U. R., "Application of WRF with different Cumulus Parameterization Schemes for Precipitation Forecasting in a Tropical River Basin", *In Proceedings of the 13th Asian Congress of fluid Mechanics*, Vol. 514, December, 2010.

27. Dantanarayana, M., Herath, S. and Weerakoon, S. B., "Improving Sub Daily Scale Storm Forecasting for Kelani River Basin

Based on Temporal Distribution of Rain Events", *Journal of Climatology & Weather Forecasting*, Vol. 9, No. 1, 2021, pp. 1-9.

28. Samarasingha, S. M. T. C., Sandaruwan, M. S., Sampath, D. S. and Neluwala, N. G. P. B., "Dynamic Downscaling of Rainfall Data for Deduru Oya River Basin using WRF Weather Model", *Engineer: Journal of the Institution of Engineers, Sri Lanka*, Vol. 54, No. 02, 2021, pp. 69-75.

29. Jeworrek, J., West, G. and Stull, R.,"Evaluation of cumulus and microphysics parameterizations in WRF across the convective gray zone", *Weather and Forecasting*, Vol. 34, No. 4, August, 2019, pp. 1097-1115.

30. Kessler, E., "On the Distribution and Continuity of Water Substance in Atmospheric Circulations. In: On the Distribution and Continuity of Water Substance in Atmospheric Circulations", *Meteorological Monographs*, Vol. 10, 1969.

31. Chen, S. H. and Sun, W. Y, "A One-Dimensional Time Dependent Cloud Model", *Journal of the Meteorological Society of Japan*. Vol. 80, No. 1, 2002, pp.99-118.

32. Hong, S. Y. & Lim, J. O. J., "The WRF Single-Moment 6-Class Microphysics Scheme (WSM6)", *Asia-Pacific Journal of Atmospheric Sciences*, Vol. 42, No. 2, April, 2006, pp. 129-151.

33. http://www. emc. ncep. noaa. gov/mmb/mmbpll/spring2001/tpb/, Visited, 2021/12/05.

34. Wicker, L. J. and Wilhelmson, R. B., "Simulation and Analysis of Tornado Development and Decay within a Three-Dimensional Supercell Thunderstorm", *Journal of the Atmospheric Sciences*, Vol. 52, No. 15, 1995, pp. 2675-2703.

35. Orr, A., Listowski, C., Couttet, M., Collier, E., Immerzeel, W., Deb, P. and Bannister, D., "Sensitivity of Simulated Summer Monsoonal Precipitation in Langtang Valley, Himalaya, to Cloud Microphysics schemes in WRF", *Journal of Geophysical Research: Atmospheres*, Vol. 122, No. 12, June, 2017, pp. 6298-6318.

36. Kain, J. S., "The Kain–Fritsch Convective Parameterization: An Update", *Journal of Applied Meteorology*, Vol. 43, No. 1, 2004, pp. 170-181.

37. Vaidya, S. S. & Singh, S. S., "Applying the Betts–Miller–Janjic Scheme of Convection in Prediction of the Indian Monsoon", *Weather and Forecasting*, Vol. 15, No. 3, 2000, pp. 349-356.

38. Grell, G. A. and Devenyi, D., "A Generalized Approach to Parameterizing Convection Combining Ensemble and Data Assimilation Techniques", *Geophysical Research Letters*, Vol. 29, No. 14, July, 2002, pp. 38-1.

39. Glotfelty, T., Alapaty, K., He, J., Hawbecker, P., Song, X. and Zhang, G., "The Weather Research and Forecasting Model with Aerosol–Cloud interactions (WRF-ACI): Development, Evaluation, and Initial Application", *Monthly weather review*, Vol. 147, No. 5, May, 2019, pp. 1491-1511.

40. Kuo, H. L., "Further Studies of the Parameterization of the Influence of Cumulus Convection on Large-Scale Flow", *Journal of Atmospheric Sciences*, Vol. 31, No. 5, July, 1974, pp. 1232-1240.

41. Gilliland, E. K. and Rowe, C. M., "A Comparison of Cumulus Parameterization Schemes in the WRF Model", *In Proceedings of the 87th AMS Annual Meeting & 21th Conference on Hydrology*, Vol. 2, January, 2007.

42. Sonkaew, T., Cumwan, S., Kanta, W. and Macatangay, R., "Finding the Optimum Microphysics and Convective Parameterization Schemes for the WRF Model for LPRU, Thailand", *In Siam Physics Congress 2016 Proceedings, Thailand*, 2016, pp. 243-253.

43. Hong, S. Y. & Lim, J. O. J., "The WRF Single-Moment 6-Class Microphysics Scheme (WSM6)", *Asia-Pacific Journal of Atmospheric Sciences*, Vol. 42, No. 2, April, 2006, pp. 129-151.

44. Mlawer, E. J., Taubman, S. J., Brown, P. D., Iacono, M. J., Clough, S. A., "Radiative Transfer for Inhomogeneous Atmospheres: RRTM, A Validated Correlated-k Model for the Longwave", *Journal of Geophysical Research: Atmospheres*, Vol. 102, No. D14, 1997, pp. 16663-16682.

45. Dudhia, J., "Numerical Study of Convection Observed during the Winter Monsoon Experiment using a Mesoscale Two-Dimensional Model", *Journal of Atmospheric Sciences*, Vol. 46, No.20, 1989, pp. 3077-3107.

46. Mukul Tewari, N. C. A. R., Tewari, M., Chen, F., Wang, W., Dudhia, J., LeMone, M. A., Mitchell, K., Ek, M., Gayno, G., Wegiel, J., Cuenca, R. H., "Implementation and Verification of the Unified NOAH land Surface Model in the WRF Model (Formerly Paper Number 17.5)", *In 20th Conference on Weather Analysis and Forecasting/16th Conference on Numerical Weather Prediction*, 2004, pp. 11-15.

47. Jimenez, P. A., Dudhia, J., Gonzalez-Rouco, J. F., Navarro, J., Montavez, J. P., Garcia-Bustamante, E., "A Revised Scheme for the WRF Surface Layer Formulation", *Monthly Weather Review*, Vol. 140, No. 3, March, 2012, pp. 898-918.

48. https://www2.mmm.ucar.edu/wrf/users/namelist_best_prac_wps.html, Visited, 2021/07/27.