

Evaluate WRF-based Lightning Potential Index (LPI) lightning parameterization over Sri Lanka during second inter-monsoon in 2018

Avaliar a parametrização de relâmpagos do Índice de Potencial de Raios (LPI) baseado em WRF sobre Sri Lanka durante a segunda inter-moção em 2018

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ABSTRACT

It is important to develop accurate and reliable lightning prediction system that can be contributed towards the safety of life, both concerning forecasting for the public safety and safety of aviation and electrical power. This study aims to evaluate WRF-based Lightning Potential Index(LPI) lightning parameterization and its applicability for predicting lightning over Sri Lanka during the second inter-monsoon. The WRF-ARW model 3.9.1 was used to produce predictions for three lightning events with various physical parameterization schemes with two nested domains with a resolution of 12km and 4km respectively. The model simulated LPI values were evaluated using the Earth Networks Global Lightning (ENGLN) dataset. Results show corresponding lightning simulations were produced with spatial distribution aligned with ground-based lightning data. Results consistently show a high correlation of the LPI index with an hourly CG flash rate over the three cases. Moreover, the WRF model was able to capture the lightning using LPI in Sri Lanka, suggesting that it can be used operationally to predict lightning potential region.

Keywords: lightning prediction, LPI, Sri Lanka, WRF model.

RESUMO

É importante desenvolver um sistema de previsão de raios preciso e confiável que possa contribuir para a segurança da vida, tanto em relação à previsão para a segurança pública quanto para a segurança da aviação e da energia elétrica. Este estudo tem como objetivo avaliar a parametrização de relâmpagos baseada no Índice de Potencial de Raios (LPI) do WRF e sua aplicabilidade na previsão de relâmpagos sobre o Sri Lanka durante a segunda inter-moção. O modelo WRF-ARW 3.9.1 foi usado para produzir previsões para três eventos de raios com vários esquemas de parametrização física com dois domínios aninhados com uma resolução de 12 km e 4 km, respectivamente. Os valores de LPI simulados pelo modelo foram avaliados usando o conjunto de dados Earth Networks Global Lightning (ENGLN). Os resultados mostram que as simulações de raios correspondentes foram produzidas com distribuição espacial alinhada aos dados de raios baseados em terra. Os resultados mostram consistentemente uma alta correlação do índice LPI com uma taxa horária de relâmpagos de CG nos três casos. Além disso, o modelo

WRF foi capaz de capturar os relâmpagos usando o LPI no Sri Lanka, sugerindo que ele pode ser usado operacionalmente para prever a região potencial de relâmpagos.

Palavras-chave: previsão de relâmpagos, LPI, Sri Lanka, modelo WRF.

1 INTRODUCTION

Lightning is a most grievous and oppressive weather phenomenon and is often accompanied by a severe thunderstorm, which under the circumstances with potentially lethal consequences for human life, and significant damage to critical infrastructure sectors. Since the direct and indirect effects of lightning as a natural hazard, lightning forecasting has become an important and necessary factor in the prevention and mitigation of natural hazards. The impact of lightning normally depends on our understanding of the characteristics of lightning, forecasting capabilities, and also the validity of the precautionary steps that can be launched. However, quantitative analysis of natural hazards, such as the amount of death, resulted in weather system reveals that lightning accidents come to a considerable place. Predicting a thunderstorm is one of the most difficult, demanding and grievous weather phenomena in the meteorology. Thundershowers are in scale in temporal and spatial distribution(Perler & Marchand, 2009) and the chaotic nature of the atmosphere has made it is hard to predict than the large scale phenomenon (Elmore, Stensrud, & Crawford, 2002).

Through the years, various studies have been conducted in most places all over the world, but not in Sri Lanka. It is important to implement a lightning forecasting system in Sri Lanka. As well as, the accuracy of lightning forecasting has become an important factor in day-to-day activities by improving the planning and management of climate-sensitive activities, especially in agriculture, construction, electrical power, and aviation industry. Totally, 263 deaths have been reported to the Department of Meteorology in Sri Lanka from 2010 to 2019, due to lightning. The most these deaths are impacted to the people who are working in agriculture sector.

Thus, it needs to effective and reliable lightning prediction and important requirement for the vulnerable field such as agriculture, construction, electrical power, and aviation. A numerous casualties and considerable damages such that lightning has become one of the greatest grievous and formidable natural hazards due to the frequent occurrences of lightning events. So it is important to develop a lightning prediction

system that can be contributed towards the safety of life, both concerning forecasting for the public safety and safety of aviation and electrical power.

2 METHOD

2.1 STUDY AREA

Sri Lanka is an island placed near to the northern portion of the Indian Ocean within the tropical region within the bounds of $5^{\circ} 55'$ to $9^{\circ} 51'$ north latitude and within the bounds of $79^{\circ} 42'$ to $81^{\circ} 53'$ east longitude. The middle portion of the country is a complex upland with a maximum height about 2500 m (Figure 1). The central part of the country has interwoven topographical profiles such as peaks, basins, valleys, and plateaus. The rest of the country is a usually flat area with several separate mountains.

Figure 1: Topographical elevation of Sri Lanka.



Source: https://www.researchgate.net/publication/327946284_Sensitivity_Study_of_WRF_Numerical_Modeling_for_Forecasting_Heavy_Rainfall_in_Sri_Lanka

Lightning occurrence in Sri Lanka shows peaks within the Inter-monsoon seasons (March & April and October & November). During this period particularly afternoon or evening, the most favourable atmospheric condition is available to develop convective clouds (Cumulonimbus) over most parts of Sri Lanka.

2.2 METHOD AND MATERIALS

In this study, the WRF model was used for producing various predictions for selected lightning events with various physical parameterization schemes.

Two nested domains were used as in Figure 2.

Figure 2: The outer domain 12-km with the inner domain of 4-km



Source: Author's research

The model configuration included two nested domains with a resolution of 12km and 4km as shown in figure 2, with 92 x103 and 102 x144 grid points, respectively.

In this study, four different microphysics schemes were used, which have six types of hydrometeors to investigate the sensitivity of the microphysics process to the model. WSM6, WDM6, Thompson and Morrison 2-Moment were used in this research work for simulating the lightning events in Sri Lanka.

Table 1 Model and two nested domain configurations

Configuration	Outer Domain	Inner Domain
WRF version	3.9.1	
Horizontal grids	92 x103	102 x 144
Grid spacing (km)	12	4
Vertical grid	42 layers/Top 50hPa	
Integration time(s)		
Radiation	RRTM Longwave Scheme for long wave radiation and Dudhia Shortwave Scheme for shortwave radiation	
Microphysics	WSM - 6/WDM- 6/THOM/MORISSON	
Lightning option	LPI (3)	
Surface layer	MMS Similarity Scheme	
Land surface	Unified Noah Land Surface Model	
Planetary boundary layer	Yonsei University (YSU) scheme Integration time: every time step	
Land use and topography data	modis_30s+5m	modis_30s+2m
Cumulus	BMJ/Grell 3D	BMJ/Grell 3D/NA
Initial boundary condition	Global Forecasting System (GFS) Model Forecast Fields (27km resolution, NCEP)	

Table 1 describes details of the WRF model and two nested domain configurations.

Source: Author's research

2.3 SELECTION EVENTS

The thunderstorms and lightning in Sri Lanka is the most common weather phenomenon during the inter-monsoon seasons. Thunderstorms are the most important water source in the dry zone of the country where most agricultural land is spread out. For this study, 03 significant events were selected within the second inter-monsoon in 2018.

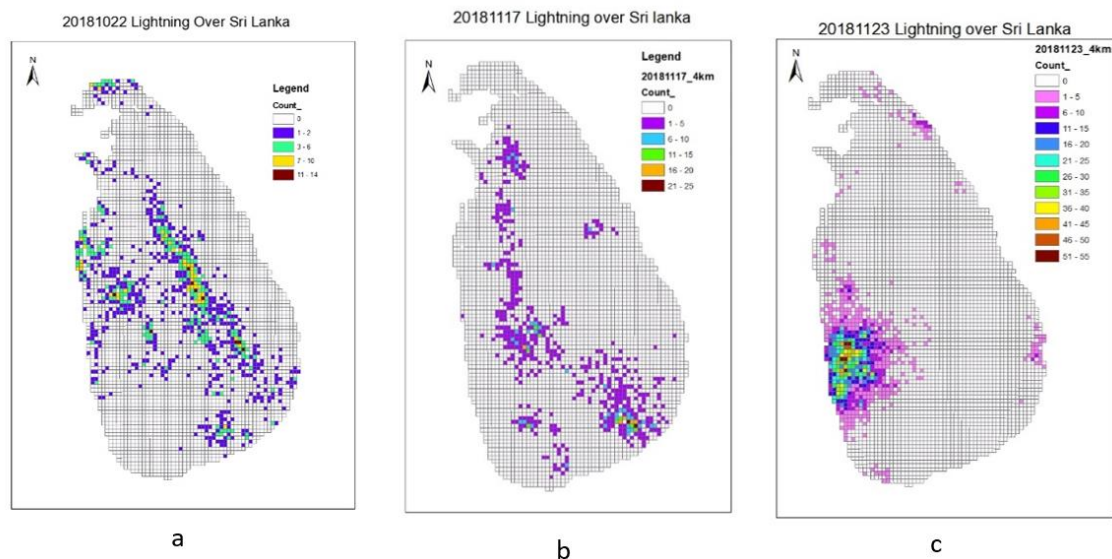
The selected lightning events are shown in Table 2.

Table 2 The selected lightning events within the second Inter-Monsoon in 2018

Event	Date	Season	Maximum rainfall
1	22 October 2018	Second inter-monsoon	127.0mm
2	17 November 2018	Second inter-monsoon	110.0mm
3	23 November 2018	Second inter-monsoon	110.0mm

Source: Department of Meteorology Sri Lanka

Figure 3: (a) Observed CG lightning flash density on 22nd October, (b) on 17th November and (c) on 23rd November in 2018

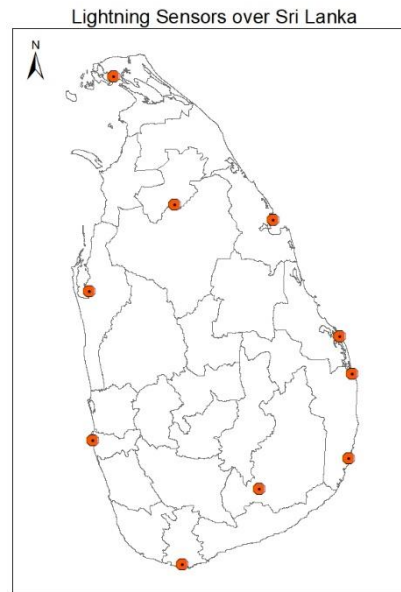


Source: Author's research (Lightning data from ENGLN and Created by author using GIS)

2.4 OBSERVATION NETWORK

Data from ten (10) ground-based Earth Networks Global Lightning (ENGLN) sensors over Sri Lanka (Figure 4) available to compare with model prediction values for LPI to verify the model performance.

Figure 4: Ground based ENGLN sensors over Si Lanka



Source: Author's research (Sensor location coordinates from ENGLN and created by author using GIS)

The Earth Networks Global Lightning Network (ENGLN) consists of more than 1500 wideband (1Hz to 12Mhz) sensors deployed in more than 40 countries around the world. Lightning generates electromagnetic pulses that propagate in all directions. Multiple ENGLN sensors detect and record these pulse waveforms, and transmit them to a central server for processing. The waveform arrival time, shape and, the signal amplitude is used to determine the event type (IC or CG), polarity, peak current, and location including latitude, longitude, and height.

2.5 LIGHTNING POTENTIAL INDEX (LPI)

Yair et al., (2008) and Lynn et., (2010) were introduced a new parameter for predicting lightning called Lightning Potential Index (LPI). Now it has become a lightning parameterization for the WRF model. It can be defined as the volume integral of the total mass flux of ice and liquid water within the “charging zone” (0 to -20 °C) in a developing thundercloud. It indicates the potential to separate electrical charges in the “charging zone” through the non-inductive ice graupel mechanism of the developing thundercloud. The LPI can be derived from the model simulated grid-scale vertical wind component and the mass ratios of cloud ice, liquid water, graupel, and snow.

The LPI transforms with time since it is calculated from the dynamical and microphysical model fields at each time step and in every domain grid point. It has some value within the charging zone, and furthermore the LPI for a particular model grid be only non-zero when a majority of cells within a five grid radius of that grid point has a vertical velocity > 0.5 m/s, indicating the growth phase of the thunderstorm. The LPI can be defined as

$$\text{LPI} = 1/V \iiint \varepsilon w^2 dx dy dz$$

W is the vertical wind component in ms^{-1} and V is the model unit volume. The integral is computed within the cloud volume from the freezing level to the height of the -20°C isotherm, the model computed mass mixing ratio for liquid water, snow (q_s), graupel (q_g), cloud ice (q_i), and ε is a dimensionless number which has a value between 0 to 1 defined as

$$\varepsilon = 2(Q_l Q_i)^{0.5}/(Q_l + Q_i),$$

Where:

Q_l is the total liquid water mass ratio in (kg/kg) and Q_i is the ice fractional mixing ratio in (kg/kg) defined as

$$Q_i = q_g [((q_s q_g)^{0.5}/(q_s + q_g)) + ((q_i q_g)^{0.5}/(q_i + q_g))]$$

Here:

ε is a scaling factor for the cloud updraft and attains a maximal value when the mixing ratio of super-cooled liquid water (Q_l) and of the ice species (Q_i) are equal (Q_i also obtains a maximal value when the mass mixing ratio of ice, snow, and graupel are equal). It signifies that charge separation requires all these ingredients to operate synergistically within the charging zone, as shown by many experiments summarized by Saunders (2008).

2.6 DATA ANALYSIS METHODS

A contingency table such as Table 3 is produced the number of hits, misses, false alarms, and correct negatives. It considers each grid point lightning as a one lightning event.

Table 3 Model forecast and observation contingency

		Observed		
		Yes	No	
Forecast	Yes	Hits	False alarm	Forecast yes
	No	Misses	Correct non-events	Forecast no
		Obs. yes	Obs. No	Sum total

Source: Statistical Methods in the Atmospheric Sciences (D.S. Wilks)

2.6.1 Probability of Detection (Hit Rates) (POD)

The POD considers only the occurrence events. It gives the ratio of observed lightning events that events were correctly forecasted by the model.

$$POD = \frac{\text{Hits}}{(\text{Hits} + \text{Misses})}$$

Source: Statistical Methods in the Atmospheric Sciences (D.S. Wilks)

The Hit rate value is between 0 and 1. The perfect score is 1.

2.6.2 Thread Score (TS)

The threat Score (or critical success index) used as a standard verification method. This sensitive to both missed and false alarm. It is a good general score for evaluation or comparison of the model forecast. It is only considered with the forecast that is important while neglecting correct rejections.

$$TS = \frac{\text{Hits}}{(\text{Hits} + \text{Misses} + \text{False alarms})}$$

Source: Statistical Methods in the Atmospheric Sciences (D.S. Wilks)

The threat score value is between 0 and 1. The perfect score is 1.

2.6.3 Correlation (r)

Pearson Correlation coefficient gives the strength of a linear relationship between two variables. The values of the correlation coefficient are between -1 and 1.

2.6.4 Combined Score for Lightning Prediction

It is wise to implement a combined skill score from above said statistical score by getting together to summarize the result. It is implemented by organizing these scores: the probability of detection, threat score, and correlation coefficient described earlier. The purpose of this score is to better understand the overall model capable of forecasting and organize the all result together for the help of taking a decision.

$$\text{Combined Score} = \text{mean} (\text{POD} + \text{TS} + r)$$

According to the definitions of sections 3.5.1, 3.5.2, and 3.5.3 the ranges of TS and POD are between 0 and 1. The value of the correlation is between -1 and 1 as its definition.

Table 4 Summary of combined score

Parameter	Method of Evaluation	Value range	Perfect score
Overall performance of lightning prediction	Combined score	-0.33~1	1

Source: Author's research

The combined score for evaluating the model performance is shown in the above table. This skill score used for overall model performance to find out the best model configurations.

2.7 EXPERIMENT DESIGN

Model simulations of this experiment carried out on the next 24 hours from 0000UT to 0000UTC. The model simulations were carried out to predict the LPI for evaluating cloud to ground lightning flash variation with various microphysical and cumulus parameterization. The WRF-ARW model simulations were initialized at the time as 0000UTC on the relevant date. The GFS model 0.25-degree data were used for getting the lateral boundary and initial conditions

2.7.1 Sensitivity of Physical Parameterization

Eighteen (18) simulations were carried out to predict the values for LPI for evaluating the physical parameterization for testing lightning prediction and the model configuration is shown as Table 5. The microphysical and cumulus parameterization used

to investigate the sensitivity of WSM6, WDM6 and Thompson microphysics with Betts-Miller-Janjic, Grell-3 and explicit cumulus parameterization.

Table 5 Summary of experiments

Experiment	Microphysics		Cumulus parameterization	
	Domain-1	Domain-2	Domain-1	Domain-2
Simulation 01	WSM6	WSM6	BMJ	BMJ
Simulation 02	WSM6	WSM6	BMJ	Without CP
Simulation 03	WDM6	WDM6	BMJ	BMJ
Simulation 04	WDM6	WDM6	BMJ	Without CP
Simulation 05	THOMPSON	THOMPSON	BMJ	Without CP
Simulation 06	THOMPSON	THOMPSON	Grell3D	Without CP

Source: Author's research

3 RESULTS & DISCUSSION

This chapter was focused on the results of LPI values predicted model simulations using the above described methodology. Evaluation of model-simulated LPI from different microphysical and cumulus parameterization with the cloud to ground lightning flash presents its effect on the predictability of LPI for three (03) events.

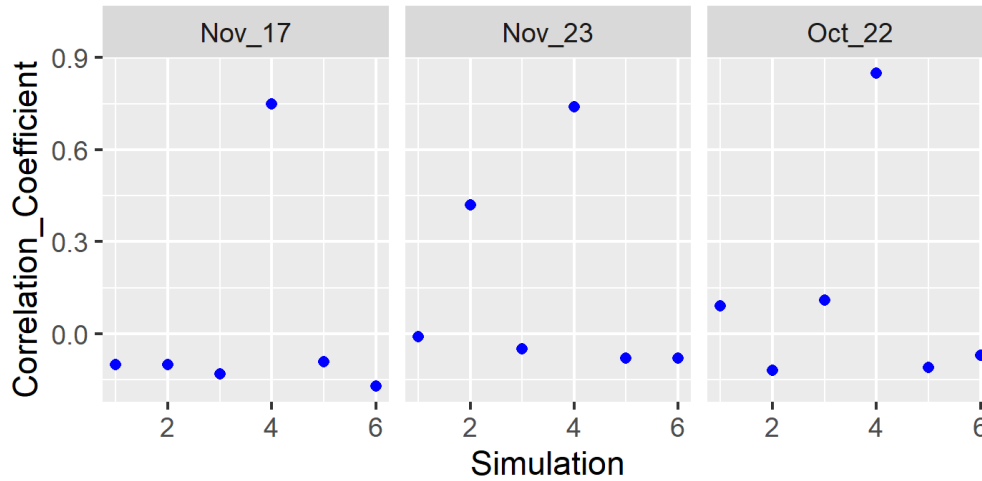
3.1 RESULTS

3.1.1 Impact on Physical Parameterization with LPI

LPI gives the measurement of the ability to charge generation and separation that leads the way to the occurrence of lightning in convective thunderstorms. The model predicted the hourly area averaged LPI were evaluated with hourly cloud to ground lightning flash rate.

3.1.1.1 Correlation

Figure 6 : Pearson correlation coefficient (r) in between hourly lightning flash rate and hourly average LPI



Source: Author's research

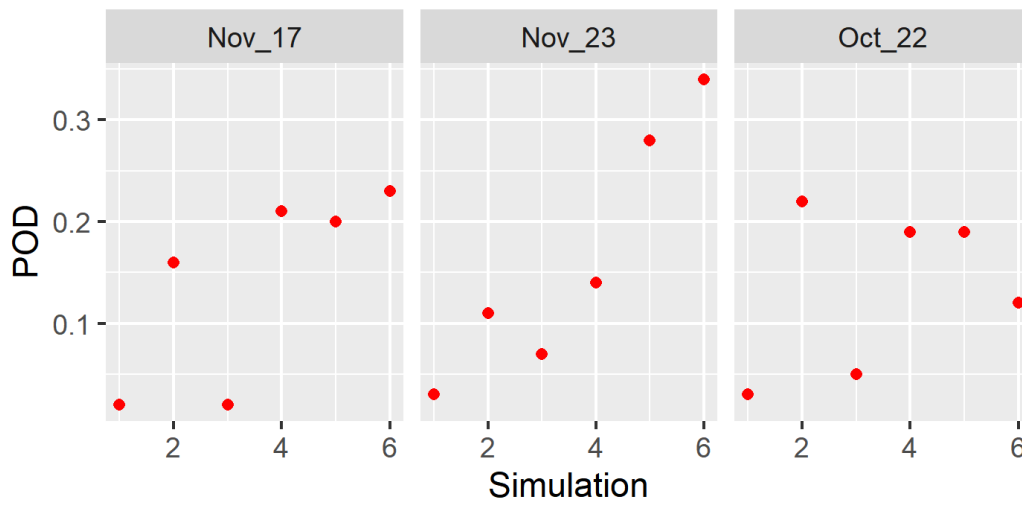
Figure 6 shows the values of Pearson correlation in between hourly lightning flash rate and hourly average model produced LPI. The values of correlation coefficient were in between -0.14 to 0.56. The 4th simulation shows values for LPI in between 0.27 to 0.85. For 4th simulation has acceptable correlation coefficient (r) values for all other events.

The correlation coefficient does not measure accuracy. It tells how much of the variance of the observations is to the correct forecast. The above figure clearly shows the 4th simulation has a moderate uphill linear relationship for all events. Among these simulations, 4th simulation has a strong linear relationship between the LPI and hourly flash rate.

Among these microphysics, WDM6 microphysics scheme shows a significant linear relationship than other microphysics. The strength of a linear relationship does not only depend on the microphysics scheme but also depends on the cumulus physics scheme. According to the analyze, BMJ has significant values for a linear relationship than other cumulus physics.

3.1.1.2 Probability of Detection (POD)

Figure 7 : Proportion of detection (POD) in between hourly lightning occurrence and hourly average LPI



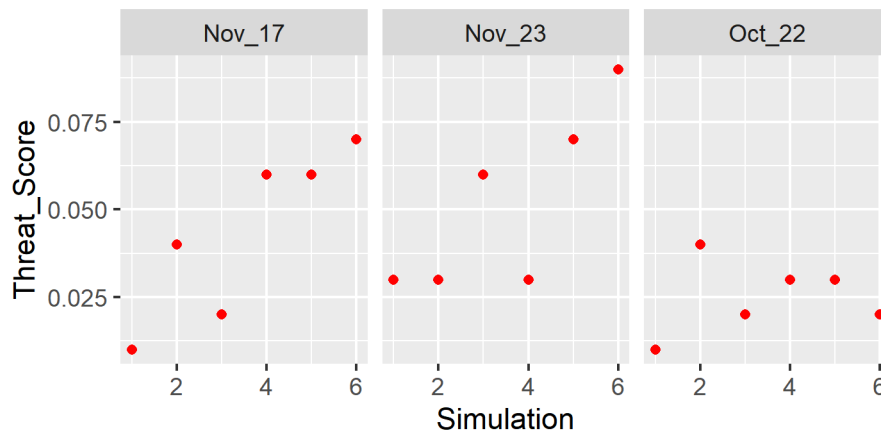
Source: Author's research

Each graph represents the probability of detection and threat score with model simulation. The value of the POD and TS indicated by the position of shapes. The continuous values were between 0 and 0.63. None of the simulations shows significant POD values for every event.

The high POD values in figure 8 are indicated that the model success in predicting the lightning occurrence while low POD values indicate the failure of predicting the occurrence of lightning. Except for a few events, all other events have a low score of POD.

3.1.1.3 Threat Score (TS)

Figure 8: Proportion of detection (POD) and Threat Score (TS) in between hourly lightning occurrence and hourly average LPI



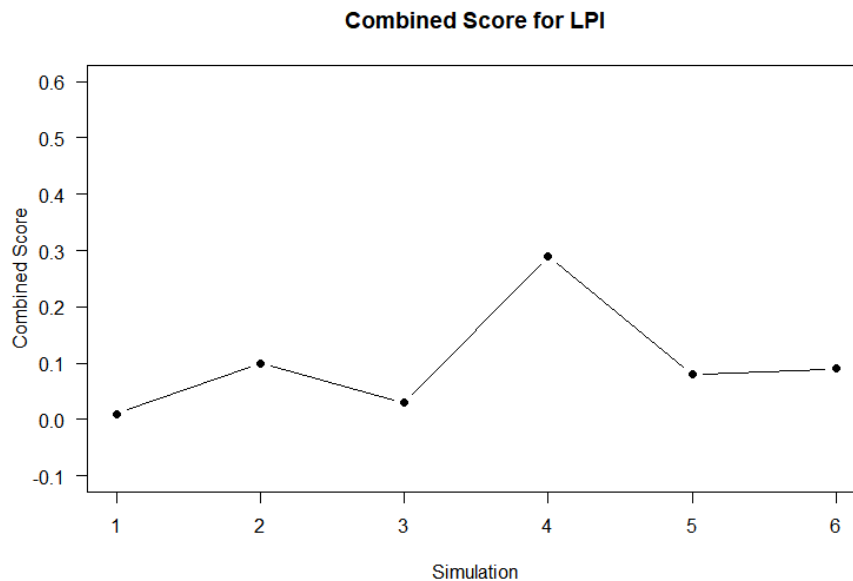
Source: Author's research

The TS for the hourly lightning flash rate and model produced hourly average LPI has shown in figure 8. Each graph represents the threat score with model simulation.

The values for TS are lying in the vertical axis was between 0 and 0.08. Every simulation shows significant low TS values for every event. The highest of TS shows by 6th combinations for the event on 23rd November. Here considered only available observed events while neglecting correct negatives. In this experiment the values of threat scores are very low because of observed lightning was not spread the whole country. Within one day, lightning available in a specific area. Therefore, many negative corrections are available in the model forecast. But those negative corrections are neglected.

3.1.1.4 Combined Score

Figure 9: Combined Score in between hourly lightning occurrence and hourly average LPI



Source: Author's research

The combined score represents the overall performance of model lightning prediction by LPI. It is easy to compare and select the most suitable physical parameterization. This graph clearly shows among these simulations the 4th is suitable for predicting lightning using LPI. It includes WDM6 microphysics and BMJ cumulus physics without cumulus physics for the fine domain.

The LPI indicates the strength of the vertical wind component within the developing thundercloud and it indicates the ability for charge generation and separation based on mass mixing ratios of ice and liquid water in the “charge zone” (0°C to -20°C) of the cloud. It is derived using the simulated grid-scale vertical wind component and model simulated hydrometeor mass mixing ratios of liquid water, cloud ice, snow, and graupel. WSM6 and Thompson can predict six hydrometeors, such as rain water, water vapour, cloud ice, cloud water, snow, and graupel (Skamarock et al., 2008). Apart from those hydrometers, the WDM6 can be predicted the number concentrations for rainwater and cloud together with a predicted variable of cloud condensation nuclei (CCN) number which gives for the possibility of exploring aerosol effects on cloud properties, and also the precipitation method. However, the microphysics processes within the WDM6 microphysics, even though applied same formula in those two microphysics, they work different way from those in the WSM6 microphysics because of the predicted number

concentrations of cloud water and rainwater, that directly affect to the value of LPI. The WSM6 microphysics scheme, predict the mass mixing ratio of the 6 class hydrometeors. The WDM6 microphysics scheme follows the WSM6 scheme and includes the same predict water substance variables. However, this is a double moment scheme and it can predict both mass mixing ratio and number concentration of the warm phase hydrometeor species. Therefore, the WDM6 microphysics scheme gives good results for LPI more than the WSM6 microphysics scheme.

The cumulus physics scheme is compulsory for coarser grid size. If the horizontal grid space is small enough (4kmx4km), the convection process resolved by the microphysics and, therefore, a cumulus scheme may not need further.

The result shows an acceptable relationship between the hourly average LPI and the hourly lightning flash rate for the 4th simulation. Lightning predicting capability is highly dependent on the both microphysics schemes and cumulus physics schemes. The WDM6 microphysics scheme has shown the best acceptable result. BMJ cumulus physics has shown the best acceptable result while Grell 3D cumulus physics was showing the worse results. According to the correlation coefficient and combined score value 4th simulation (WDM6 microphysics for both domain and BMJ cumulus physics schemes for outer domain and without cumulus physics for inner domain) was the best simulation among these eight simulations. It has greater than 0.5 values for the correlation coefficient for the eight events from out of eleven events.

Lightning Potential Index (LPI) is a useful index for predicting the probability of lightning occurrence and to detect the potential area for thunderstorms in large.

3.2 DISCUSSION

According to the analysed lightning prediction with LPI for different physical parameterization revealed that the different physical parametrization has different skill to predict LPI parameter. All results can be summarized as follows.

Table 6 : Values of combined score for LPI

Simulation	Combined Score value
	LPI
1	0.01
2	0.1
3	0.03
4	0.29
5	0.08
6	0.09

Source: Author's research

In the above table, 6 is presented the values of the combined score for LPI. Here the values of threat scores are very low for all parameters because calculating the threat scores neglect the negative corrections. During the second inter-monsoon, thundershowers and lightning are localized features generally spread limited area. Therefore, lightning is not available in all other areas of the country. Then, there are many negative corrections. It was highly affected by the value of the threat score and the combined score. These results give the 4th simulation is the best simulation to predict lightning using LPI. In 4th simulation includes WDM6 microphysics for both domain and BMJ cumulus physics for the outer domain and without CP for the fine domain.

Combined score values for LPI have spread in a wide range. Only 4th simulation gives some higher scores. The value of LPI depends on the values of vertical wind component and mass mixing ratio of snow, cloud ice, and graupel. These variables are affected by the Cloud Condensation Nuclei (CCN) in the atmosphere. The vicinity of Sri Lanka is very rich in CCN and only WDM6 considers the CCN concentration while other microphysics are neglecting CCN concentration. This may be the main reason that WDM6 could be produced better values for LPI for this study domain. Then 4th simulation produced a higher value of combined score than other simulations.

Yair et al., (2010) revealed that LPI is a good index to predict lightning compared to the thermodynamics indices like K-Index and CAPE. In their experiment, they used 1km resolution for fine domain and Thompson microphysical scheme and Kain-Fritsch cumulus physics scheme to investigate Mediterranean storms. According to their results, there was a high correlation (0.74, 0.71 and 0.51) between the LPI and lightning flash

rate. Again, Yair et al., (2010) revealed that LPI could be used to predict lightning for resolution of the 4km domain. Here, they used the WSM6 microphysics scheme for calculating the required parameters to compute the LPI. Fiori et al., (2016) also revealed that the LPI is a good parameter for forecasting lightning. They used 1km grid resolution and the WSM6 microphysics scheme and the grid space has chosen for the last two domains (5km and 1km) make the model able to solve explicitly.

In the above said experiments, they widely used the WSM6 microphysics scheme and WDM6 used in one experiment. In my experiment, WSM6 did not give significant results for LPI. Unlike WSM6, the WDM6 predicts the number concentrations for rainwater and cloud together with a prognostic variable of cloud condensation nuclei (CCN) number which allows for the possibility of investigating aerosol effects on cloud properties, and the precipitation process. Sri Lanka is an island, therefore it has higher CCN concentration than other countries This may be a reason WDM6 gives significant values than other microphysics schemes for correlation coefficient and combined score.

According to the results, cumulus physics has not much affected to the values of LPI. According to the atmospheric condition during the second inter-monsoon and geographical and topographical features of the study domain, thundershowers and lightning are localized systems that spread within a few kilometres (2-4 km). Thus, cumulus option was not much affected this kind of small system. It is highly affected the system larger than 10 km.

The charging process of the thunder cloud still depends on hypothesis. Collisions of very small ice crystal and graupel is one of the methods charge generation within the thunder cloud. Ice crystals charge positively and going upward of cloud while graupel charges negatively and going downward of a cloud. Therefore, charge generation depends on the updraft wind within the charging zone. Normally, the range between 0⁰C and -40⁰C consider as the charging zone of a thunder cloud. When calculating the value of LPI, it considers only the range of 0⁰C to -20⁰C and it created for the middle latitude areas. This actual range may vary from region to region of the earth. In further studies, it can be changed to find a better charging zone such as 0⁰C to -30⁰C, 0⁰C to -40⁰C and -10⁰C to -30⁰C to the relevant study area. It will help to improve the LPI according to the region.

4 CONCLUSION

4.1 CONCLUSION

In this study, six model simulations with the WRF model were carried out for 03 selected events in Sri Lanka during the second Inter-monsoon season in 2018, in order to examine the best microphysics scheme to predict the occurrence of lightning. LPI were examined under the six model simulations as potential lightning predictors that could be used to predict the occurrence of lightning.

The LPI is the most directly related parameter with lightning occurrence. According to the results, LPI shows acceptable value of correlation coefficient with flash rate for the WDM6. It is a good indication to identify the probability of lightning occurrence and vulnerable area. But the value of correlation coefficient has spread between 0.27 and 0.85 with WDM6. It indicates the relationship between lightning flash rate and the LPI depends on the conditions of the atmosphere. Lightning Potential Index (LPI) is a useful index for predicting the probability of lightning occurrence and to detect the potential area for thunderstorms in large. However, to investigate this new parameter more experiments are needed.

4.2 RECOMMENDATIONS

I considered lightning events during 2018 with limited physics options. It is better to consider lightning events for several years with more physics options. Thus, suggest that more studies of lightning events during several years are needed, and testing more physics schemes including radiation, boundary layer, and land surface physics to find the better combinations of physics for predicting the occurrence of lightning. Future research work with different charging zone may help to improve the LPI especially for the tropics.

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