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Markov Chain Probability Models to Describe Bi-modal Rainfall Pattern in Sri Lanka

Eranga M. Wimalasiri[1] and A.D. Ampitiyawatta[1*]

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ABSTRACT

Purpose: *Sri Lanka is a tropical island with prominent four monsoonal seasons. The rainfall pattern of the country follows a bi-modal distribution with two peaks centred on two growing seasons. Model the bi-model rainfall distribution of Sri Lanka using the Markov probability chain model was the objective of this study.*

Research Method: *Both first and second-order Markov probability models were developed for Anuradhapura, Badulla, Hambanthota and Katunayake using daily rainfall data for 1981–2011 period and the locations were selected to cover the major parts of the country. The model fit was done using Instat Statistical Programme.*

Findings: *Both first and second-order Markov models successfully described bi-modal distribution of rainfall. In general, both transitional probabilities in the first order (p_rd and p_rr) and three transitional probabilities of second-order except rainfall after dry day and rainy day (p_rrd) followed a bi-modal pattern with two peaks. The sum of the logs of the rainfall amount (lr) and the amount of rainfall on rainy days (r_mean) also showed two peaks for two growing seasons. In both models, stations in the dry zone showed higher agreement in the simulated rainfall.*

Research Limitations: *Lack of continuous long-term rainfall data is one of the major limitations.*

Originality/ Value: *It is evident that both first and second-order Markov chain probability models are very much capable to explain the bi-modal rainfall distribution in Sri Lanka.*

Keywords: *Instat, Maha season, monsoonal rainfall, probability of rainfall, Yala season*

INTRODUCTION

Being a tropical island located between 5 and 10° North latitudes in the Indian Ocean, Sri Lanka does not experience seasonal temperature variation (Punyawardena 2008). Therefore, rainfall variation, the amount and the pattern, is the key determinant of the agro-climatology of Sri Lanka. Around 33% of the lands in the country is used for agricultural purposes (AgroStat 2019). Annual rainfall of the country is erratic and highly variable; ranges from causing droughts due to lack of rainfall that lasts for months and periods of extreme precipitations, storms and floods (Manawadu and Fernando 2008). There is enough scientific evidence to suggest that the variability in rainfall has a direct impact on major crops in Sri Lanka such as paddy (De Silva *et al*. 2007; Dharmarathna *et al*. 2014), maize (Karunaratne and Wheeler 2015), coconut (Peiris *et al*. 2008) and Proso millet (Wimalasiri *et al*. 2017).

[1*]*Department of Export Agriculture, Faculty of Agricultural Sciences, Sabaragamuwa University of Sri Lanka, Belihuloya 70140, Sri Lanka.*
ada@agri.sab.ac.lk
https://orcid.org/0000-0001-6319-8198

Agricultural patterns across the country are related to monsoon rains at a particular time of the year. Based on the monsoon rainfall patterns, two principles and two inter monsoon seasons can be observed. South West Monsoon (SWM: June to September) and North East Monsson (NEM: December to February) are the principal monsoon seasons and First Inter Monsoon (FIM: March to May) and Second Inter Monsson (SIM: October to November) are inter monsoons (Suppiah 1996). As a result of these monsoons, rainfall in Sri Lanka typically shows a distinctly bi-modal pattern, that leads to two cropping seasons which are named as *Yala* (minor) and *Maha* (major). The low rainy *Yala* season benefits from FIM and SWM which span six months (March to September) while the *Maha* season receives rainfall from SIM and NEM (De Silva *et al*. 2007). However, the actual onset and the retreat of both seasons were defined inconsistently by different authors; *Yala* in March to September (De Silva *et al*. 2007), March to October (Wickramagamage 2015), April to August (Sonnadara 2015), May to August (Seo *et al*. 2005) and *Maha* in September to February (Chithranayana and Punyawardena 2008), September to March (Sonnadara 2015), October–February (De Silva *et al*. 2007), October to March (Zubair 2002). Therefore, statistical approaches are vital to study the bi-modal distribution of rainfall that is the base for cropping seasons in the country.

According to annual rainfall amount, the country is divided into three major climatic zones as Wet, Intermediate and Dry. The western, south-western and central parts of the country occupy the Wet Zone (rainfall >2500 mm/ year) while northern, eastern and south-eastern parts of the country cover the Dry Zone (<1750 mm rain annually). The Intermediate zone (rainfall 1750–2500 mm/ year) is located in between Wet and Dry zones. Based on the altitude, the country is further divided into three zones as Low country (< 300 m), Mid country (300-900 m) and Up country (> 900 m). The diversity of rainfall and elevation in the country creates 46 agro-ecological zones (Punyawardene 2008). Around 70% of the total annual rainfall of the country occurs during a shorter rainy season during October to January period (Punyawardena and Kulasiri 1996). With the uncertainty of rainfall pattern, the understanding of both temporal and spatial variation of rainfall is important to plan agricultural, hydro-electric, irrigation water management, drainage planning and flood mitigation activities around the country (Jayawardene *et al*. 2005; Nisansala *et al*. 2019).

Few attempts have been made to study the pattern and variability of rainfall in Sri Lanka using different approaches; Mann-Kendall trend analysis (Jayawardene *et al*. 2005; Ampitiyawatta and Guo 2009; Nisansala *et al*. 2013), regression models (Ampitiyawatta and Wijeratne 2015; Wickramagamage 2015), other statistical methods (Sonnadara 2015) and Markov probability analysis (Punyawardene and Kulasiri 1996; Perera *et al*. 2002). According to the incorporated physical realism, rainfall models can be divided into three major groups; intermediate stochastic models, dynamic models and empirical statistical models (Sanso and Guenni 1999). Empirical models fit to the available data but do not include physical features of the atmosphere into the models whereas dynamic models are mainly physically-based models. The intermediate stochastic models are a combination of both empirical and dynamic models that include physical processes of rainfall structure (Sanso and Guenni 1999).

The use of Markov chain which is a stochastic model for rainfall analysis dates back to the 1960s on which Gabriel and Neumann (1962) studied the daily rainfall occurrence at Tel Aviv. It was successfully used to study the rainfall characteristics in Sri Lanka in different geographic and timescales (Weerasinghe 1989; Dahale *et al*. 1994; Punyawardene and Kulasiri 1996; Perera *et al*. 2002; Piyadasa and Sonnadara 2010, Sonnadara and Jayawardene 2015). However, very few of the studies (Dahale *et al*. 1994; Piyadasa and Sonnadara 2010) focused on relatively complex second-order Markov model over three or more locations in Sri Lanka.

Among several approaches, a well-established second-order Markov probability chain model was used in this study. All the previous studies on Markov chain modelling in Sri Lanka used only rainfall or dry days. The novelty of this study is the use of both first and second-order Markov probabilities of rainy days and rainfall amount to describe the rainfall pattern in the country. The objective of this paper was to use the second-order Markov chain model to study the bi-modal rainfall distribution in Sri Lanka. The study also focused on the variation of transition probabilities of rainy days, rainfall amount and probability of dry spells using the fitted models.

MATERIALS AND METHODS

Location Details and Data

Considering the agroclimatic variability of Sri Lanka, four locations (Table 01) which cover major parts of the country were selected and respective daily rainfall data for 31 years (1981-2011) were collected from the Department of Meteorology. Out of the 4 stations, Anuradhapura and Hambanthota belongs to Low country Dry zone (DL), Badulla belongs to Mid country Intermediate zone (IM) while Katunayake is located in Low country Wet zone (WL). In general, all the selected locations are agricultural areas on which paddy is the major crop. The agroecological characteristics of the selected meteorological stations are summarised in Table 01.

The minimum level of data availability is up to 0.1 mm, however, that could be easily evaporated under the tropical conditions (Sonnadara and Jayewardene 2015) so that, a higher threshold value (0.85 mm) which was used in the rainfall studies in Dry Zone Sri Lanka was used to define a rainy day (Wimalasiri *et al*. 2017). Alternatively, dry day was a day with less than 0.85 mm of rainfall. In order to have the consistency, the rainfall on 29th February of 7 leap years in the study period were ignored.

Probability of Rainfall

The probability of a rainy event in any year can be expressed as *m*/*n*, when the rainy event *m* occurred within *n* number of years. Following the method developed by Stern and Coe (1982), the curved that are not normally distributed were fitted to the proportions (Bekele 2001). To ensure that, the probability *p* is transformed as,

$$f = log\left(\frac{p}{1-p}\right)$$

Therefore, f can be varied from -∝(p=0) to +∝(p=1).

If the t represents a day of a year, the function $F(t)$ is fitted to t and the fitted probabilities could be written as

$$f = exp\left[\frac{F(t)}{1+\exp\left(F(t)\right)}\right]$$

n harmonics for the function of $F(t)$ for the Fourier series is;

$$F(t) = a_0 + a_1 \sin x + b_1 \cos x + a_2 \sin 2x + b_2 \cos 2x + \ldots + a_n \sin nx + b_n \cos nx$$

on which $x = \frac{\pi t}{366}$

Table 01: Agroecological characteristics of the meteorological stations selected in the study

Name	Latitude	Longitude	Agroecological zone*	Annual rainfall (mm)*	Comment*
Anuradhapura	8.35	80.38	DL_1	>900	Main rainy season from March to May
Badulla	6.98	81.05	IM_1	>2000	Poor FIM and SWM
Hambanthota	6.11	81.13	DL_5	>650	Shortest *Maha* season of the dry zone
Katunayake	7.16	79.88	WL_3	>1700	Lowest rainfall of low country wet zone

* *Punyawardene 2008*

First-Order Markov Chain Model

In the first-order Markov chain probability model, rainfall probability of a particular day depends on the rainfall nature of the previous day; whether it is wet or dry (Sonnadara and Jayawardene 2015). If the probability of the current situation (P*xy*) in the *y* condition at *t* time changed from the previous condition of *x* at t-1 time, the transitional probabilities can be defined as,

$$P_{xy}(t) = P\{X_t = y / X_{t-1} = x\} \qquad x, y = 0, 1$$

If the rainy day is "r" and the dry day is "d", the two transitional probabilities can be written as p_0 and $(1 - p_1)$ on which p_0 denotes the probability of a rainy day with a previous dry day (p-rd) and $(1 - p_1)$ demotes the probability of a dry day with a previous rainy day (p_dr) (Sonnadara and Jayawardene 2015).

$$p_1 = Pr\{r/r\};\ (1 - p_1) = Pr\{d/r\}$$

$$p_0 = Pr\{r/d\};\ (1\text{-}p_0) = Pr\{d/d\}$$

In contrast, two other transitional probabilities can be written as p_dd (dry day followed by dry day) and p_rd (rainy day with previous dry day). However, the condition on the day-before-yesterday does not have an impact, nor change the probability of rain today in the first-order Markov model.

Second-Order Markov Chain Model

However, the probability of occurrence of rainfall depends on the condition of two previous days, in the second-order Markov chain model. Instead of the *x* and *y* in the first-order Markov model, *x*, *y* and *z* are used to describe the two previous conditions. Therefore, transitional probabilities of a rainy day in the second-order Markov model can be written as

$$P_{xyz}(t) = P\{X_t = z \mid X_{t-1} = y, X_{t-2} = x\} \qquad x, y, z = 0,1$$

Therefore, rainfall in the current date can occur either on; rainy day after two dry days (rdd), rainy day after dry and rainy day (rrd), rainy day after rainy and dry day (rdr) and rainy day followed by two rainy days (rrr). In contrast, the transitional probabilities of the dry day also depend on two previous, making a total of 8 combinations as; drr (dry day after two rainy days), drd (dry day after dry day and rainy day), ddr (dry day after a rainy day and dry day) and ddd (dry day after two dry days).

Rainfall Amount

Gamma distributions were fitted to rainfall amount as followings.

$$F(x) = \frac{\left[\frac{k}{\mu}\right]^k x^{k-1} e^{-\frac{kx}{\mu}}}{\Gamma(k)}$$

on which, k is the shape parameter, Γ is the gamma function and μ is the mean rainfall per rainy day. A Fourier curve was fitted to the mean rainfall per rainy day μ, which is later described as r_mean. It is assumed that k is persistent throughout the period and estimated from the total rainfall amount following the method by Bekele (2001). The sum of the logs of the rainfall amount was (lr) also studied.

Long-Term Dry Spells

Long term dry spells are important for agricultural planning. Generally, farmers commence cultivation with the onset of the rainy season followed by a dry spell. The dry spell acts as a fallow period in between two cropping seasons. The fitted second-order Markov model was used to study the long-term dry spells. As described previously, the fitted model includes both rainy days and rainfall amount. The probability of 7-day and 10-day dry spells over a period of 30 days centred on a particular day was studied.

Model Fit, Simulations and Analysis

Both first-order and second-order Markov chain probability modelling procedure and long-term dry spell analysis were performed using the Instat Statistical Programme (Version 3.036) (Stern *et al*. 2003). Using the same programme, daily rainfall for 31 years' period was simulated using fitted first-order and second-order Markov chain model. Both rainy days (>0.85 mm) and rainfall amount were considered in the simulations. The Prism (Version 8) was used for statistical analysis and graphing.

RESULTS AND DISCUSSION

Monthly Distribution and Rainfall Probability

The distribution of monthly rainfall for the 1981-2011 period and mean overall chance of rainfall (p_r) which were calculated using the daily rainfall data are shown in Figure 01. In each location, two peaks can be identified on which the first in April-May and the second in October-November, indicating the bi-modal rainfall distribution in Sri Lanka. The first peak and the second peak are due to the SWM and NEM respectively. Punyawardene (2008) also reported that bi-model rainfall distribution is conspicuous in the dry zone which is inherent to the region. Out of the three stations in the dry and intermediate zones, Badulla receives a considerably higher rainfall during the NEM due to the geographical location of the station (Figure 01b). Lengthy *Maha* season is a specific feature in Badulla (Punyawardene 2008). Comparatively, delayed first peak and early second peak was observed at Katunayake (Figure 01d), which belongs to the wet zone.

Other than the monthly rainfall amount, the probability of rainfall (p_r) also showed a clear bi-modal pattern of distribution (Figure 01). Both monthly mean rainfall amount and the probability of overall chance of rainfall among 4 stations were significantly different ($p < 0.05$) from each other. Being located at the dry zone, the probabilities of the overall chance of rainfall of more than half of the months in Anuradhapura (Figure 01a) and Hambanthota (Figure 01c) were lesser than 0.2. Monthly variation of the overall chance of rainfall in Katunayake (wet zone) followed a similar pattern with bi-modal distribution (Sonnadara and Jayewardene 2015).

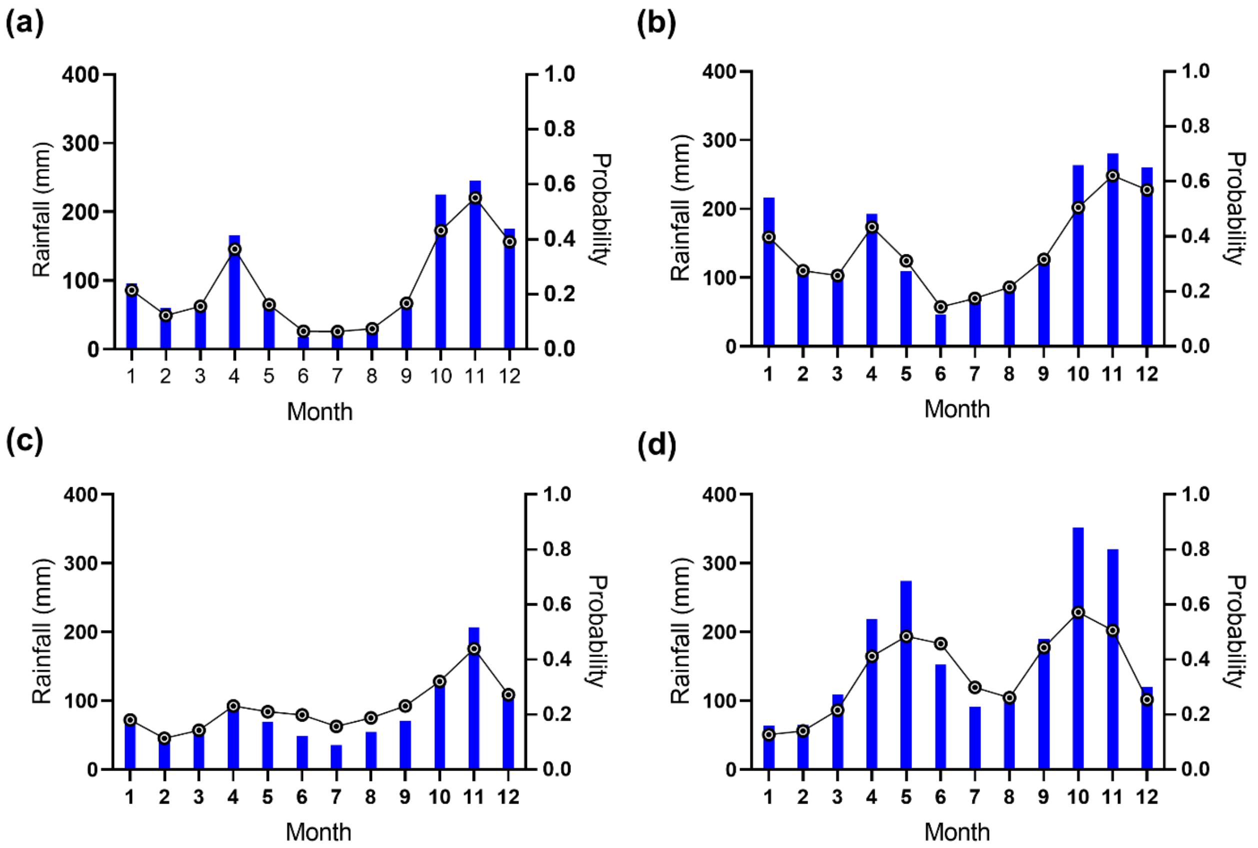

Figure 01: Distribution of monthly rainfall and the probability of rainfall (p_r) in (a) Anuradhapura, (b) Badulla, (c) Hambanthota and (d) Katunayake during the 1981-2011 period.

Variation of Transition Probabilities

The variation of observed and fitted first order and second-order transition probabilities of rainy dates calculated using 31 years of daily data are shown in Figure 02. Transitional probabilities were calculated for five-day totals to reduce the fluctuations. Due to the variation of the rainfall pattern, both first-order and second-order probabilities of rainfall showed a clear variation throughout the year. In the first-order Markov model, only two transitional probabilities related to rainy day (p_rd and p_rr) were plotted while two other transitional probabilities (p_dr and p_dd) could be derived similarly. A bi-modal distribution could be observed for all studied locations for the First-order Markov probability for a rainy day followed by a dry day (p_rd) and the fitted model was significantly different ($p < 0.05$) from each other.

In contrast, the probability of rainy day with a previous rainy day (p_rr) did not show a clear bi-modal pattern in Badulla and Hambanthota. As shown in Figure 01b, Badulla receives rainfall throughout the year that covers four monsoons. Parallel to the monsoons, four peaks were observed for p_rr in 4th week (NEM), 17th week (FIM), 31st week (SWM) and 44th week (SIM). In Hambanthota, two peaks were not clear under the general scale for all the graphs, but two peaks in p_rd can be observed which are associated with the distribution of monsoon rains as described previously.

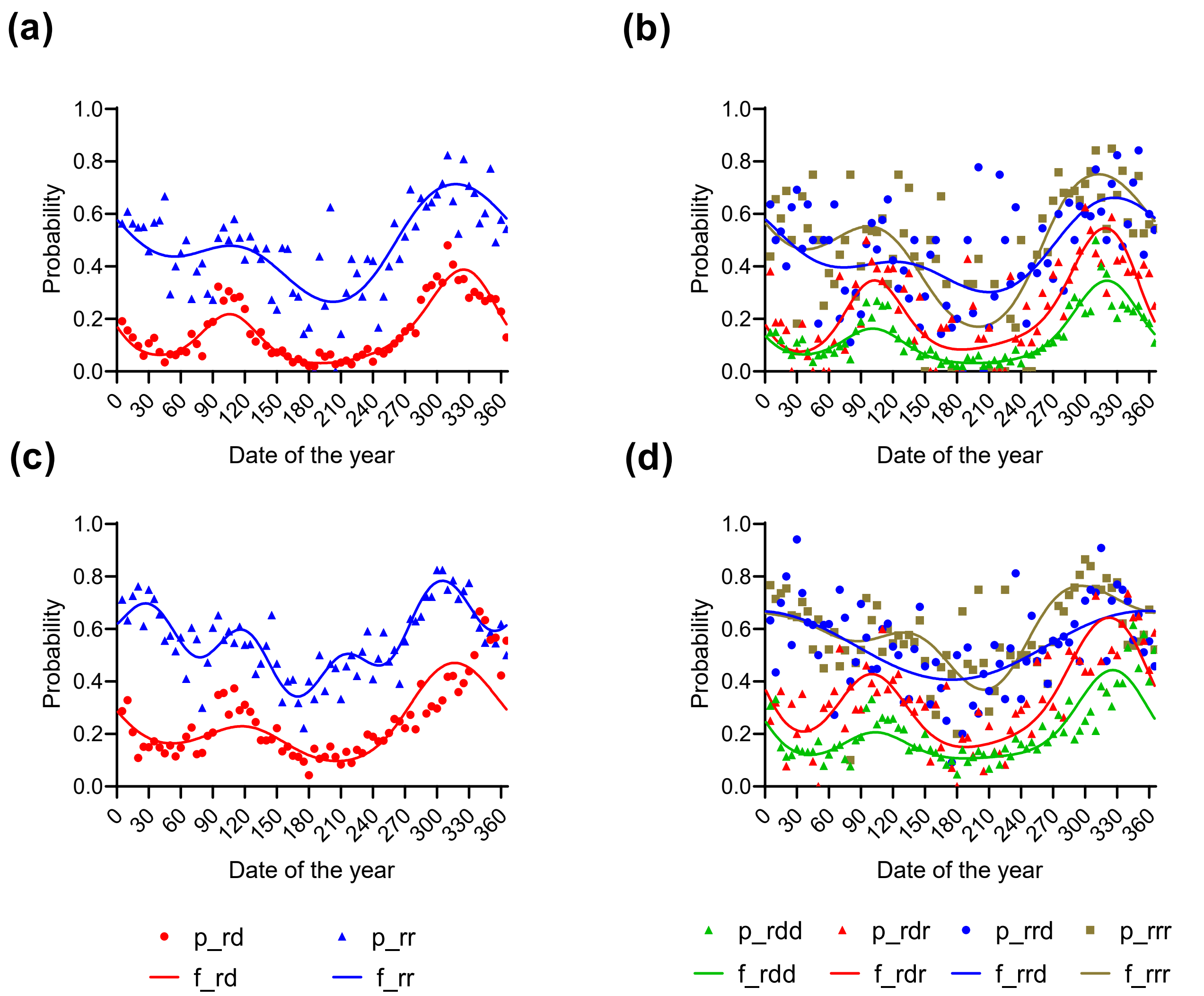

Figure 02: **Variation of first-order (a,c,e,g) and second-order (b,d,f,h) Markov chain model of Anuradhapura (a and b), Badulla (c and d), Hambanthota (e and f) and Katunayake (g and h) during 1981-2011 period. The fitted models are shown as a line in each figure while symbols represent the variation of the probabilities.**

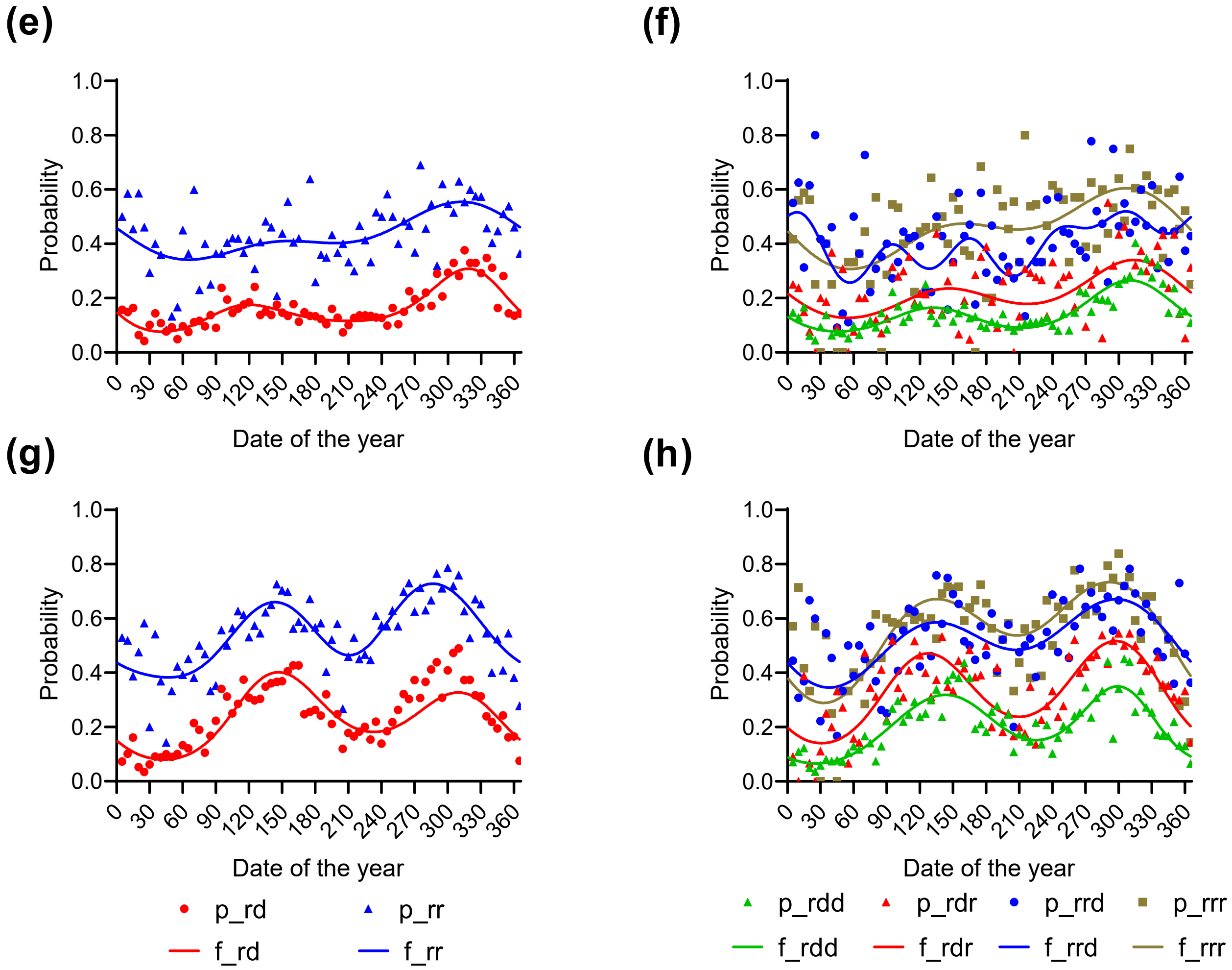

Figure 02: **(Cont.) Variation of first-order (a,c,e,g) and second-order (b,d,f,h) Markov chain model of Anuradhapura (a and b), Badulla (c and d), Hambanthota (e and f) and Katunayake (g and h) during 1981-2011 period. The fitted models are shown as a line in each figure while symbols represent the variation of the probabilities.**

In the second-order Markov model, a considerable variation was observed for both observed and fitted transition probabilities. Both p_rdd (rainy day after two dry days) and p_rdr (rainy day after rainy and dry day) showed two peaks centred on the SW and NE monsoonal period. Even though it is not a clear bi-modal, p_rrr (rainy day followed by two rainy days) also showed two peaks during the monsoon period. In general, p_rrd did not show a clear pattern except bi-modal distribution in Katunayake. A higher probability of wet days was reported on a rainy day followed by two rainy days (p_rrr). In contrast, the rainy day with two previous dry days (p_rdd) showed a lower probability in two stations studied. Results agree with the findings of Piyadasa and Sonnadara (2010) and Sonnadara and Jayewardene (2015) who described the similar probability pattern in Sri Lanka. Slight variations of the peaks can be associated with the definitions used for a rainy day, location and the period studied.

Rainfall Amount

The maximum likelihood method was used for the estimation of the shape factor of the gamma distribution. Therefore, the sum of the logs of the rainfall amount (lr) was also estimated. Other than the probabilities of rainy days, the "lr" also showed a distinct bi-modal pattern of rainfall with two peaks centred on April and October-November (Figure 03). Therefore, rainfall amount was also considered in the model development, in addition to the rainy days.

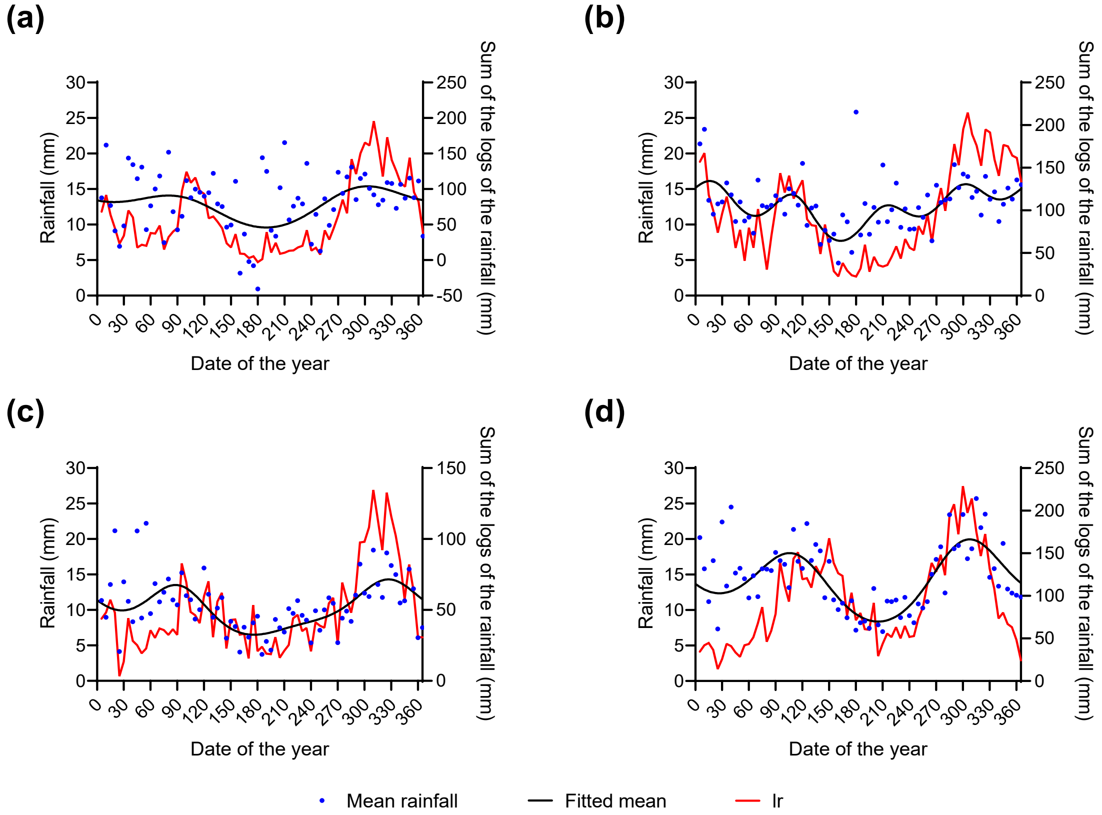

Figure 03: Variation of the sum of logs of the rainfall and mean daily rainfall using fitted second-order Markov chain model at (a) Anuradhapura, (b) Badulla, (c) Hambanthota and (d) Katunayake

The modelled rainfall amount on rainy days is shown in Figure 03. Accordingly, all the locations except Badulla which is located in the intermediate zone, showed a bi-model rainfall pattern. This is because, Badulla receives a considerably higher monthly rainfall (>100 mm) throughout the year during both seasons. Out of all, the most prominent two peaks were reported from Katunayake in the wet zone. The fitted means of the rainfall amount were significantly ($p < 0.05$) different from each other.

Transitional Probabilities and Rainfall Amount

The sum of the logs of the rainfall amount (lr) showed significant ($p < 0.05$) relationship with all the transitional probabilities at every tested location (Figure 04). Therefore, other than the mean rainfall amount, the sum of the logs of the rainfall amount can also be used to study the bi-modal rainfall pattern in Sri Lanka along with the transitional probabilities.

Simulation of Daily Rainfall Amount and Rainy Days

The rainfall amount in a rainy day and number of rainy days were simulated for 31 years period using the fitted Markov models. The Root Mean Square Error (RMSE) of the fitted first-order Markov model showed a relatively lower RMSE value compared to the second-order model for amount of rainfall and number of rainy days in each location for both seasons (Table 02). The RMSE of the simulated rainy days for both models were higher in the minor season in Katunayake (wet zone) while the values in the major season were higher in all other locations and seasons. In rainfall amount, the fitted first-order Markov model showed a relatively lower RMSE value compared to the second-order model in all the events. The descriptive statistics of observed and simulated rainy days and amount were summarised in Table 02. Since Sri Lanka receives rainfall form four monsoons, the simulated values were then compared for four seasons separately for rainy days (Figure 05) and rainfall amount (Figure 06).

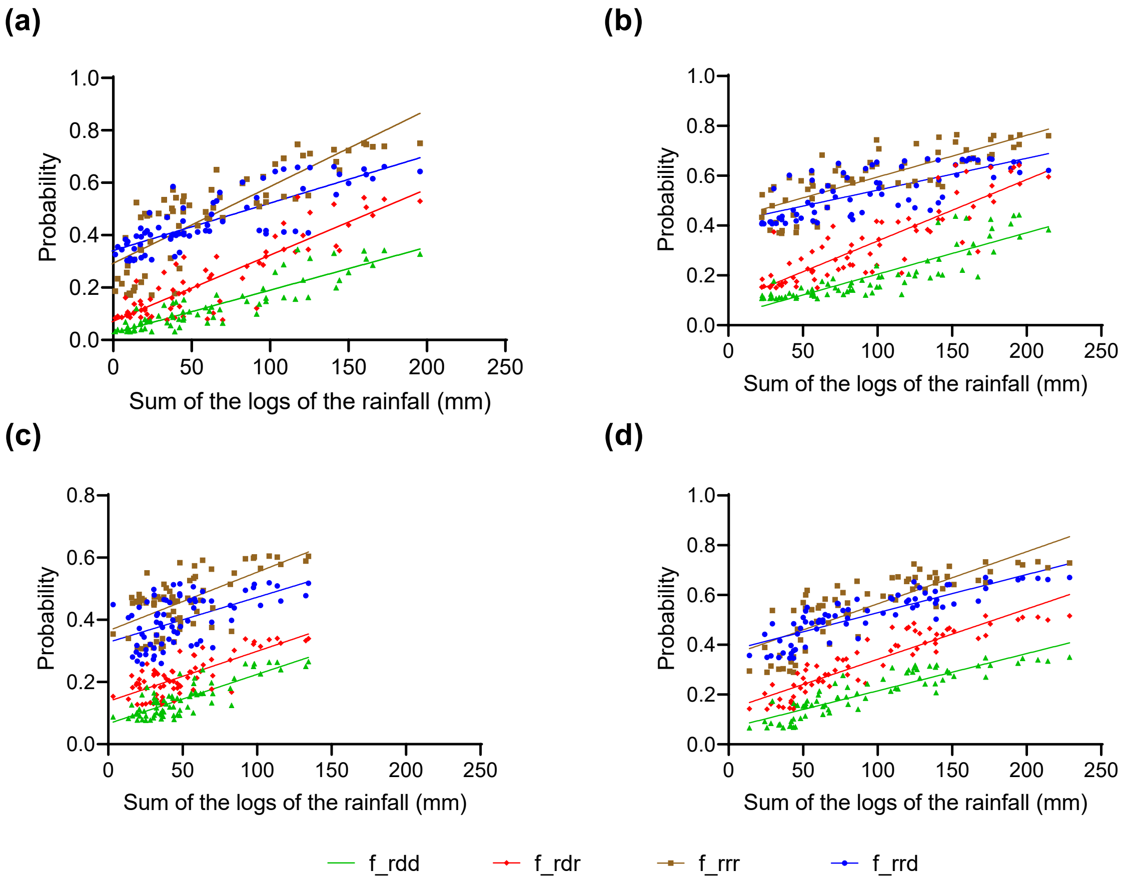

Figure 04: **Linear regression between sum of the logs of the rainfall amount (lr) and transitional probabilities in (a) Anuradhapura, (b) Badulla, (c) Hambanthota and (d) Katunayake.**

Table 02: **Summary of descriptive statistics and root mean square error (RMSE) for observed (1981-2011) and simulated number of rainy days (days) and rainfall amount (mm) during minor and major seasons**

Location	Type of data	Mean amount		Standard deviation		RMSE	
		Minor	Major	Minor	Major	Minor	Major
Number of rainy days							
Anuradhapura	Observed	32.1	51.0	6.7	12.8	-	-
	First-order	31.4	52.6	7.6	8.6	10.1	15.6
	Second-order	33.1	63.0	10.5	10.5	12.2	21.4
Badulla	Observed	56.6	72.0	9.5	11.3	-	-
	First-order	57.6	69.7	8.2	8.2	13.3	14.4
	Second-order	65.2	82.6	10.1	10.7	16.1	19.7
Hambanthota	Observed	41.2	39.8	7.9	9.7	-	-
	First-order	39.4	39.7	7.0	6.6	9.8	13.3
	Second-order	44.0	42.7	9.4	8.6	12.8	14.5
Katunayake	Observed	78.3	48.7	8.6	10.0	-	-
	First-order	75.8	47.0	9.4	7.8	13.7	13.0
	Second-order	88.3	53.7	13.1	7.5	20.1	13.5

Location	Type of data	Mean amount		Standard deviation		RMSE	
		Minor	Major	Minor	Major	Minor	Major
Rainfall amount							
Anuradhapura	Observed	455	803	124	321	-	-
	First-order	424	758.9	145	167	188	377
	Second-order	460	912.7	171	186	202	398
Badulla	Observed	734	1128	244	310	-	-
	First-order	729	1038	168	181	318	402
	Second-order	810	1225	192	208	336	417
Hambanthota	Observed	431	555	121	192	-	-
	First-order	401	502	105	129	160	257
	Second-order	443	541	121	134	168	262
Katunayake	Observed	1133	922	239	308	-	-
	First-order	1079	814.3	220	198	369	376
	Second-order	1271	955.9	268	200	429	368

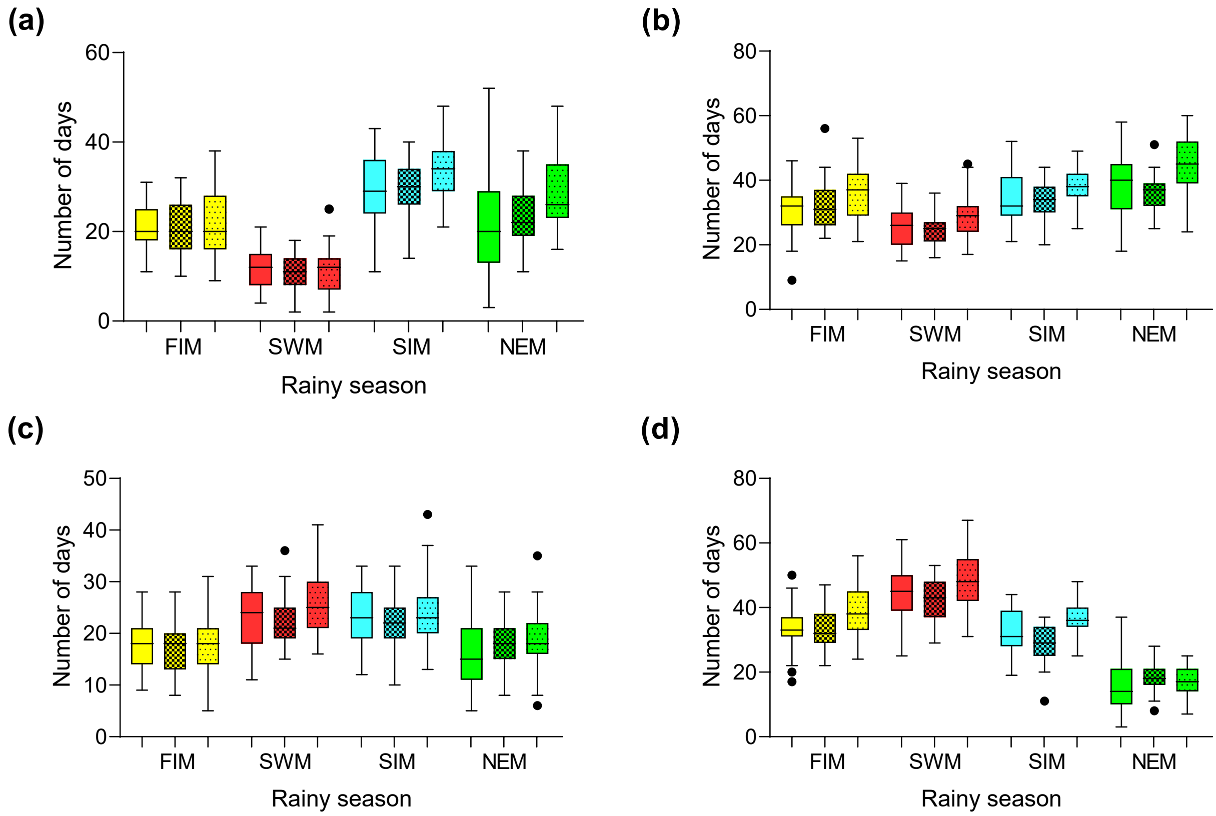

Figure 05: **Comparison of observed (shaded) and simulated number of rainy days for first-order (dark pattern) and second-order (light pattern) Markov models for four monsoonal seasons in (a) Anuradhapura, (b) Badulla, (c) Hambanthota and (d) Katunayake.**

Probability of Long-Term Dry Spells

Probability of long-term dry spells were studied by using the fitted model. Accordingly, the probability of 7-day and 10-day dry spells in a period of 30 days was plotted against the day number of the year (Figure 07). In contrast to the overall chance of rain (Figure 01), two depressions were clearly observed during the centre of two rainy seasons in every location. All the stations followed a similar pattern, while being significantly ($p < 0.05$) different among each other in both 7-day and 10-day dry spells according to the non-parametric Kruskal-Wallis test. In all the stations except Katunayake, the probability of the 7-day dry spell was higher than 0.5 during more than 75% of the days in the year. In Hambanthota, the probability was higher than 0.5 in each day of the year suggesting the higher vulnerability to the drought. The probability of 10-day dry spells at two dry zone locations (Anuradhapura and Hambanthota) was higher than 0.5 during the first peak suggesting that even during the rainy season, these locations having a higher chance to occur a dry spell.

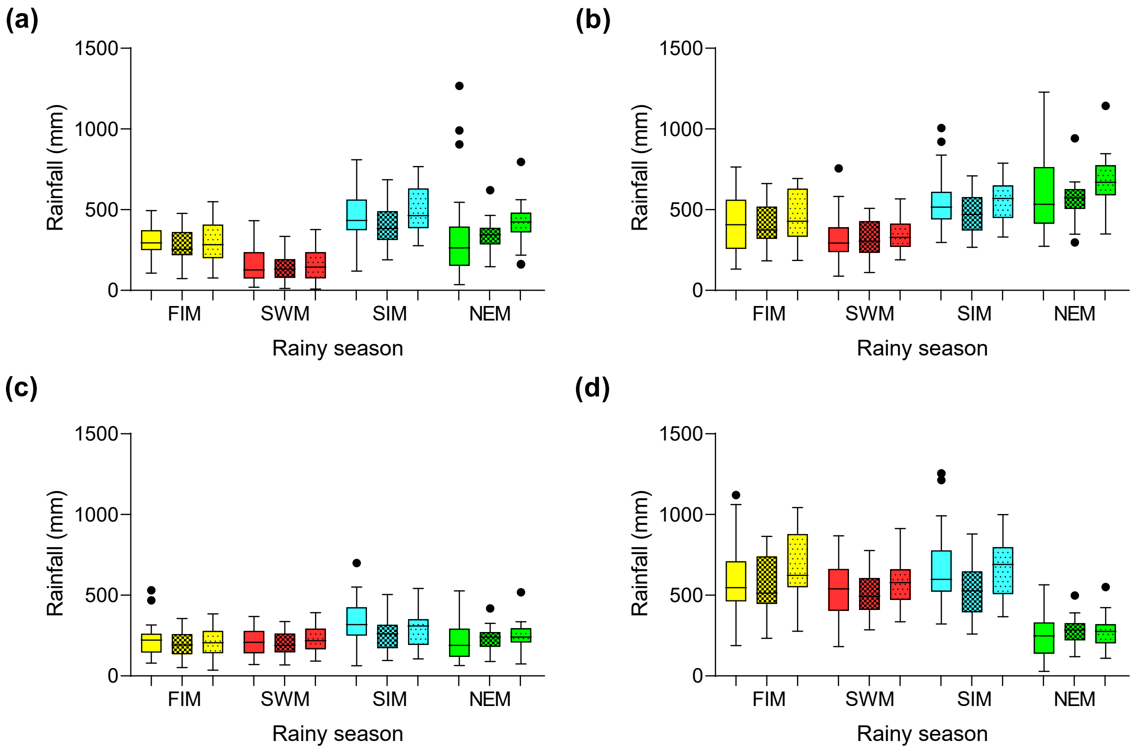

Figure 06: Comparison of observed (shaded) and simulated rainfall amount for first-order (dark pattern) and second-order (light pattern) Markov models for four monsoonal seasons in (a) Anuradhapura, (b) Badulla, (c) Hambanthota and (d) Katunayake.

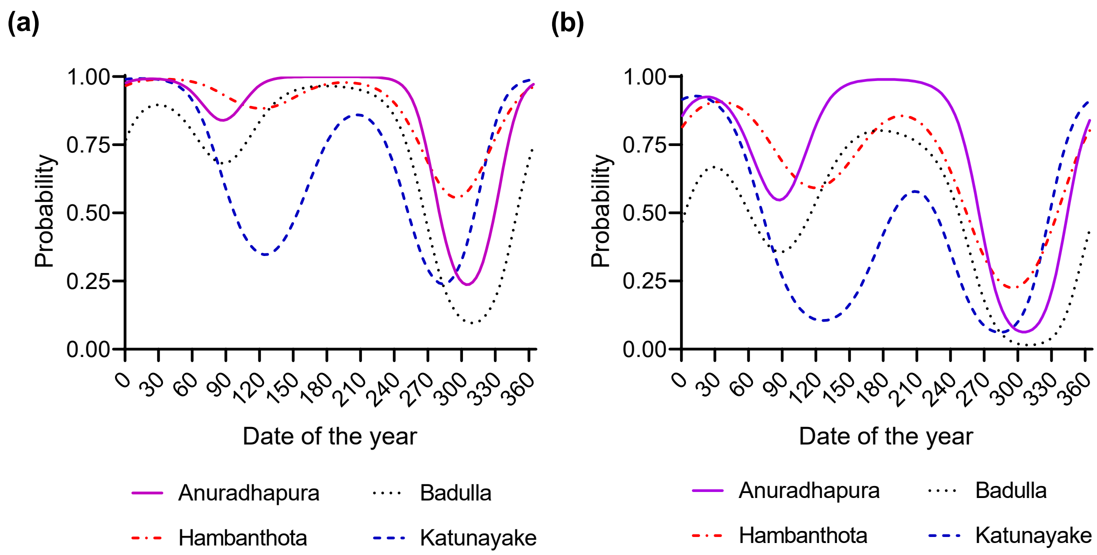

Figure 07: The probability of (a) 7 and (b) 10 dry spells in a period of 30 days centred on a particular day during the year for 1981-2011 period

CONCLUSIONS

In this study, both first-order and second-order Markov chain probability models were used to study the bi-modal rainfall distribution of four locations in Sri Lanka. Various aspects of rainfall distributed in a bi-modal pattern could be mathematically derived from Markov chain models. The transitional probabilities of both first and second-order models successfully described the wet and dry spells pattern of the country which is based on the bi-modal distribution. Other than the rainy days, the sum of the logs of the rainfall amount also used successfully to study the rainfall pattern. Both Markov models successfully simulated rainfall amount and number of rainy days. The probability of 7 and 10 days dry spells, which were studied using the fitted second-order Markov model, showed variation among locations. We conclude that both first-order and second-order Markov chain probability models can be successfully used to study the bi-modal rainfall distribution, number of rainy days and long term dry spells that are important in agricultural planning in the country.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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