

Characteristics of S-W and N-E monsoon rainfall over Salem

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The study of rainfall during various seasons in Salem (11°40'9.97"N, 78°8'27.11"E), a town in southern India has been reported in the present paper. The variability has also been discussed in terms of the accumulated rainfall (R), the number of hours of rainfall (RH) and the average rainfall (avg), as well as the percentage occurrence of very low, low, moderate, heavy, very heavy and extreme rainfall in these seasons. A particular effort has been made to determine the effect of El Nino and La Nina on patterns of rainfall. The meteorological parameters, such as cloud liquid water (CLW), precipitation water (PW) and latent heat (LH) have also been determined for various seasons. The study shows that there exists a significant degree of correlation between rainfall and these meteorological parameters. A functional relationship has also been established between the intensity of convective rainfall and CLW, PW and LH.

Keywords: Cloud liquid water, Precipitation water, Latent heat, Convective rain, Monsoon rainfall

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1 Introduction

Agricultural output makes a significant contribution to the Indian economy. A good monsoon season helps to fuel a booming economy, while a weak one results in drought leading to a significant economic loss. At the same time, the very heavy rainfall that occurs during the monsoon season produces flooding causing damage to human life and property every year in some part of India. India is characterized by two monsoon seasons, namely the south-west (S-W) and the north-east (N-E). A proper understanding of the two monsoon seasons in India is, thus, of great importance.

The latent heat (LH) budget over space and time is a very important factor in relation to monsoon and other patterns of global circulation. It has also been found that LH affects the amount of cloud liquid water (CLW) present, which in turn governs the characteristics of the weather¹. Moreover, an understanding of CLW is of immense importance to aviation safety² and weather modification. The understanding of CLW, LH and precipitation water (PW), and the measurement of these quantities in the atmosphere is necessary for understanding the formation, growth and dissipation of a cloud. There is no doubt that a study of the three parameters can improve the understanding of rainfall, and it also

appears that a better prediction of rainfall is possible with the help of these parameters together with a few other meteorological elements (*e.g.* temperature, dew point temperature, etc.). Patterns of rainfall have also been found to correlate with the phenomena of El Nino and La Nina. A study in NE Brazil shows that El Nino brings severe droughts³. In India, nine El Nino events have been reported as being associated with the occurrence of droughts, a few El Nino events have been associated with excessive rainfall, and eleven brought slightly less than normal rainfall³. There have also been reports of significant reductions in rainfall in NE and SW Australia⁴. Park *et al.*⁵ reported higher than normal rainfall in the Indian subcontinent following an El Nino event. Their study also showed that an increase in rainfall was found to occur in the latter part of the monsoon season, rather than at its peak. It is noteworthy that an El Nino event is likely to produce different effects at different Indian stations because the country consists of a number of different climatological regions and the intensity of any effect is, thus, likely to vary from station to station. In the present study, an attempt has been made to determine the effect of El Nino and La Nina events on patterns of rainfall over Salem, a city in the southern peninsula of India. The study has also investigated cloud liquid water (CLW), precipitation water (PW) and latent

heat (LH) at various atmospheric levels⁶ over Salem, the inter-relationships between these parameters and the functional relationships between them and the intensity of convective rainfall. The analyses of rainfall for both monsoon seasons for Salem have also been presented.

Salem, itself is a small town in the northern central part of Tamil Nadu, which is the southernmost state of the Indian subcontinent. It is affected by two prominent monsoon seasons, namely S-W (June-September) and N-E (October-December), the former being preceded by the pre-monsoon months from March to May. The city is surrounded by hills and dotted by hillocks and often encounters low to moderate rainfall from March to November and some light rain in December. Most rainfall events occur during the late afternoon or early evening. However, this tropical city has no full-fledged weather station, nor can the city boast any balloon launching station to monitor meteorological elements in the upper atmosphere. Under these circumstances, precipitation radar (PR) and the TMI (TRMM Microwave Imager) onboard Tropical Rainfall Monitoring Mission (TRMM) satellite seem to provide a good opportunity to study weather phenomena at this station. The validations of TRMM-estimated rainfall using ground-based observations show a good match⁷. The validation of TRMM estimated rainfall using ground truth data in Calcutta, a city in eastern India, also shows that annual TRMM estimated rainfall data match ground truth data rather well but the monthly and daily agreement is not as good⁸. The analysis of hourly rainfall data obtained from the India Meteorological Department (IMD) has been described in order to investigate the variability of the S-W and N-E monsoon in terms of the accumulated rainfall and the high, low and intermediate rainfall. Convective rainfall and meteorological elements of the upper atmosphere such as CLW, PW and LH, as obtained from TRMM, have also been used to establish the functional relationships involved. The validity of the relationships has also been assessed using an F-test at 5% level of significance.

2 Data base

The hourly rainfall data for Salem has been obtained from the IMD for the period 1996-2006; and CLW, PW, LH and convective rainfall data from TRMM satellite. These data are the level 2 products 2A12 (ref 6) of the passive Microwave Imager (TMI)

onboard TRMM and were obtained in Hierarchical Data Format (HDF). TMI measures the microwave radiation emitted by the earth's surface, cloud and rain drops. The radiation so measured estimates the temperature of the emitter based on Planck's radiation law. The information of temperature from the scene as derived from various channels of TMI, along with cloud model quantifies rainfall. For each instantaneous field of view, TRMM provides a set of parameters at 14 levels⁶ on a pixel by pixel basis, *i.e.* for each pixel these parameters are given at 14 vertical layers. The values of CLW are in the range 0.00 - 10.00 gm⁻³ and are multiplied by 1000 and stored as 2-byte integers⁶. The values of PW are in the range 0.00 - 10.00 gm⁻³ and are multiplied by 1000 and are stored as 2-byte integers⁶. The values of LH are in the range -256° - 256°C/h. These values are multiplied by 10 and stored as 2-byte integers⁶. The raw data in HDF format were converted to ASCII format prior to further analysis.

3 Results and Discussion

In order to determine any difference between S-W and N-E monsoon rainfall, the present study was carried out using the classification of rainfall intensity given in Table 1. The percentages of occurrences of rainfall for the years 1996-2006 using this classification has been presented in Fig. 1. It may be seen that for both the S-W and the N-E monsoon seasons, it is low rainfall that occurred most frequently with 27.92 - 37.50% of the total S-W rainfall occurrences and 29.34 - 41.30% of the total N-E rainfall occurrences. Nevertheless, there are exceptions to this observation in some years. In 2002 and 2006, intermediate rainfall occurred most frequently in the S-W case, and in 1996, very low rainfall occurred most frequently in the S-W case. For the N-E case, the exceptions have been found in 1996 and 2006, when very low rainfall occurred most frequently. Extreme rainfall was found to occur only very rarely at Salem. Extreme rainfall had occurred only in the S-W case in 1996, 2000 and 2005 and in the N-E case only in 1997

Table 1—Classification of rainfall intensity

Rainfall	Intensity, mm h ⁻¹
Very low	<0.25
Low	0.25-1.0
Intermediate	1.0-4.0
Heavy	4.0-16.0
Very heavy	16.0-50.0
Extreme	>50.0

and 2005. It is noteworthy that 1996 and 2000 were La Nina years^{9,10}. Hence, it may be seen that La Nina brought extreme rain fall to Salem.

Figure 1 further shows that very low rainfall persisted for longer duration in the N-E monsoon as compared to the S-W monsoon. Low and intermediate rainfall conditions persisted for longer duration for the N-E monsoon in 50% of cases and for the S-W in 50% of cases. The total number of hours of heavy and very heavy rainfall was always higher for S-W than for N-E except for 1998 and 2005.

Table 2 shows the total rainfall in a year and the corresponding rainfall for the N-E, S-W and pre-monsoon seasons. It is found from Table 2 that the S-W monsoon brings more rainfall in Salem than the N-E and the pre-monsoon months, except in 2004 when the pre-monsoon months brought more rainfall in Salem; and in 1997 and 2005, when the N-E monsoon brought more rainfall.

Figure 2 shows the contribution of each rainfall intensity category to the total rainfall over Salem. It is found from Fig. 2 that heavy rainfall contributes the most to the total rainfall over Salem in all the seasons, except few cases.

Similar study by the authors over the nearby stations shows that low to very low rainfall is the most predominant over Bangalore (12.58°N, 77.38°E) (figure not shown). Over Chennai (13.04°N, 80.17°E), low rainfall intensity is found to be predominant (figure not shown), and over Trivandrum (8.29°N, 76.59°E), it is very low rainfall that occurs most frequently (figure not shown). In all the three

Table 2—Rainfall over Salem

Year	Total rainfall, mm			
	Pre-monsoon	S-W	N-E	Yearly
1996	201.8	691.8	390.0	1283.6
1997	142.4	433.7	502.0	1078.1
1998	148.1	569.9	455.8	1173.8
1999	200.3	366.7	348.7	915.7
2000	165.2	714.0	367.4	1246.6
2001	174.0	620.7	243.1	1037.8
2002	123.5	342.9	138.5	604.9
2003	203.9	407.1	235.7	846.7
2004	416.4	257.7	227.7	901.8
2005	194.4	467.9	638.1	1300.4
2006	226.2	472.7	326.8	1025.7
Total	2196.2	5345.1	3873.8	11415.1
Average	199.65	485.9	352.16	1037.74

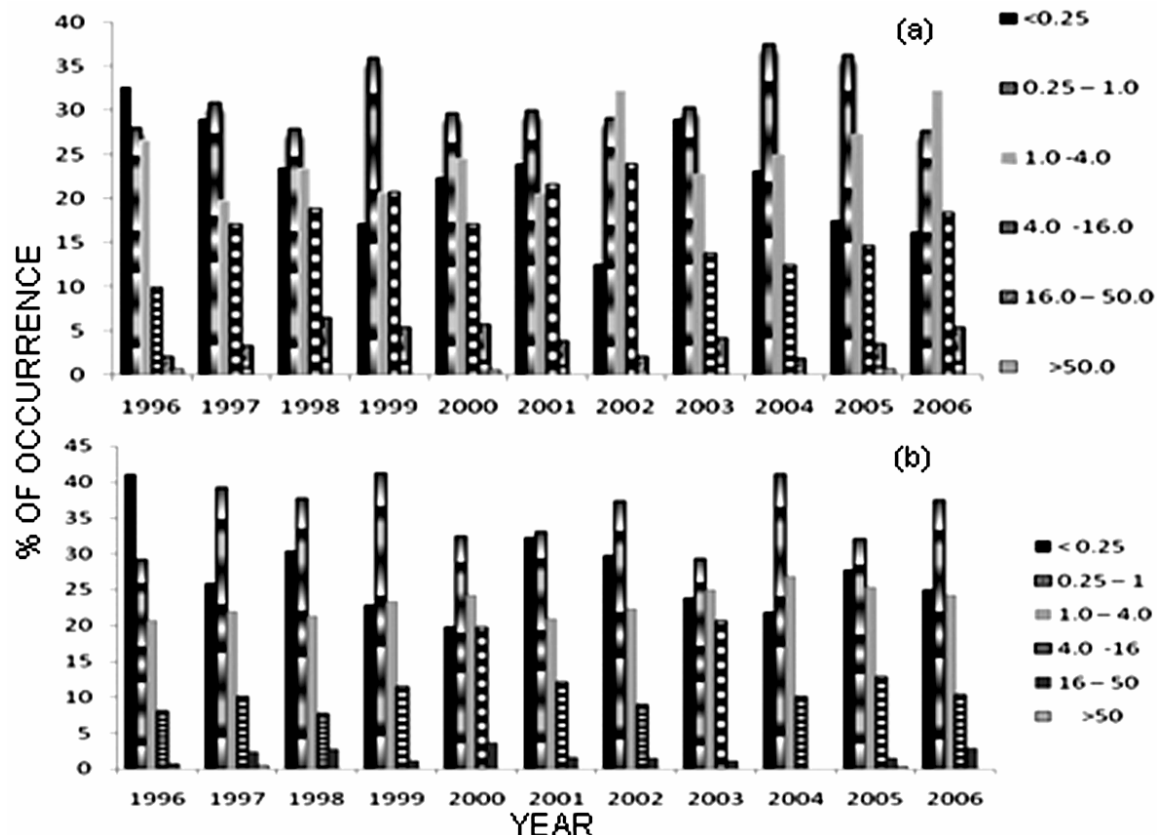


Fig. 1—Percentage of occurrence of rainfall for different rainfall rate intervals at Salem: (a) South-West and (b) North-East monsoon

stations, it is heavy rainfall intensity that contributes the most to the total rainfall.

3.1 Rainfall and influence of El Nino and La Nina

Within the context of the occurrence of El Nino (1994-1995, 1997-1998, 2002-2003, 2004-2005, 2006-

2007, 2009-2010) and La Nina (1995-1996, 1998-1999, 2000-2001, early 2006, 2007-2008) (refs 9-12), the study of rainfall (Table 2) at Salem during 1996-2006 shows that the El Nino of 2002, 2004 and 2006 brought below normal yearly rainfall prior to its occurrence. Average of 11 year rainfall over Salem is

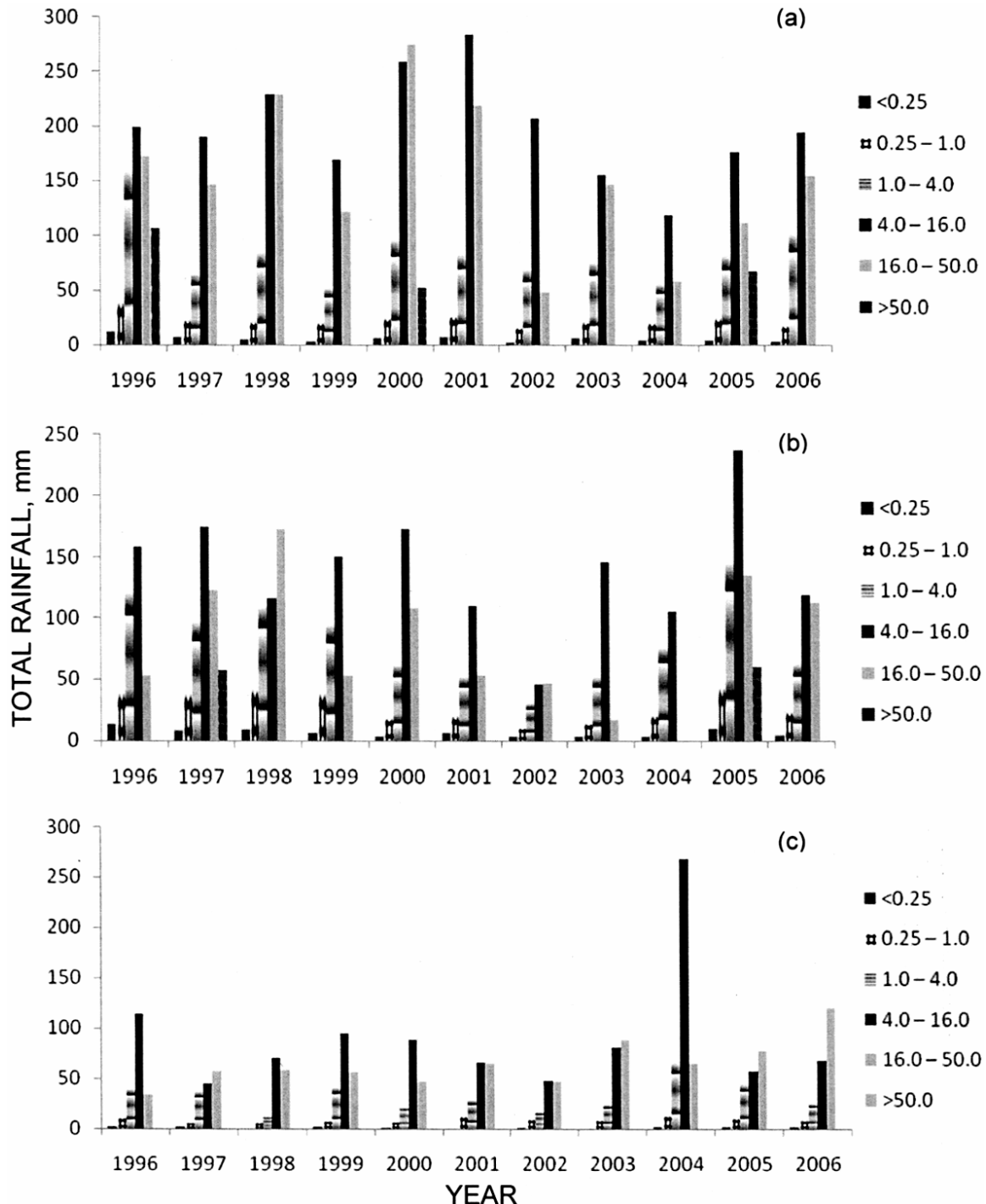


Fig. 2—Contribution of various rainfall intensities to total rainfall over Salem: (a) South-West; (b) North-East; and (c) pre-monsoon

found to be 1037.74 mm (Table 2). It is also found that La Nina of 1998 and 2000 brought above normal rainfall in Salem prior to its occurrence. The effect of El Nino and La Nina on individual monsoon season is also found from Table 2. It is seen that the El Nino of 1997, 2002, 2004 and 2006 brought less rainfall prior to its occurrence in the S-W and N-E monsoon. La Nina is found to bring higher than normal rainfall in the S-W and N-E monsoon in 1998 and 2000. However, the pre-monsoon months preceding both a La Nina and El Nino event faced below normal rainfall in some years and above normal in the other. It is noteworthy that not all below normal rainfall years had witnessed an El Nino, and not all above normal rainfall years had witnessed a La Nina. Previous studies show that the majority of the El Nino events resulted in weak Indian monsoon rainfall^{13,14}. The study of Mishra¹⁵ shows that in India weak rainfall is associated with El Nino and La Nina years are associated with excess Indian summer monsoon rainfall¹³.

3.2 Vertical profiles of CLW, PW and LH

The values of CLW, PW and LH have been obtained at various levels (Table 3) as measured by TRMM⁶. These values and the corresponding altitude values of the levels in km have been fitted to different models, *viz.* cubic, linear, exponential, s, logistic, logarithmic, inverse, quadratic, compound, growth and power in order to find out if there exist any functional relationship between the two. The validity of the relationships has also been assessed using an F test at the 5% level of significance. The results of the analysis are shown in Table 4 for few days. The analyses for other days show similar results (not shown in the paper).

It may be seen from Table 4 that CLW has a cubic relationship with height, irrespective of month. The observed variation of PW with height shows that with increasing height, PW first increases from a non-zero value to reach a peak at 0.5-1.5 km, and then it gradually reduces again at heights greater than this. PW is found to vary with height following a cubic relationship, irrespective of day and month (Table 4).

The vertical profiles of LH show an oscillatory trend, irrespective of day and month. The occurrence of peak values of CLW, PW and LH is shown in Table 4. Tables 3 and 4 show that the maximum values of CLW are found mostly at heights of 2.5-3.5 km. Also, PW attains its peak at 0.5-1.5 km. LH absorption peak occurs at the earth's surface, while the maximum heat emitted is at a height 2-3 km in

June and July, while between August and October, the LH emitted is a maximum at different levels on different days (Table 4). The studies show that the level of occurrence of peak CLW and LH is very much significant in climatology as it characterizes the convective / stratiform dominance over surface rainfall¹⁶. Steiner & James¹⁷ showed that the vertical profile of LH is different for the two types of precipitation. Moreover, knowledge of CLW, PW and LH at various levels of the atmosphere helps in quantifying surface rainfall¹⁶.

3.3 Convective rainfall vs CLW, PW and LH

In order to make assessment of whether CLW, PW and LH can be predictors of convective rainfall, the values of daily total CLW, total PW and total LH from surface up to 18 km and convective rainfall have been fitted to different models, *viz.* linear, cubic, power, exponential, growth, logistic, logarithmic, s, quadratic, compound and inverse. The validity of the relationships has also been assessed using an F-test at the 5% level of significance. The result is shown in Fig. 3.

It may be seen that convective rainfall has a cubic relationship with the total CLW available in the atmosphere in October 2007 [Fig. 3(a)] and a quadratic relationship in June 2007 (Fig. not shown). In June 2007, a cubic relationship is more suitable between convective rainfall and total PW (Fig. not shown), whereas in October 2007, the intensity of convective rainfall is directly proportional to the total PW available in the atmosphere [Fig. 3(b)], which implies that as the total PW increases, the intensity of the convective rainfall also increases. The study shows that

Table 3—Vertical profiling layers

14 Vertical profiling layers (PW/CLW)		14 Vertical heating levels	
Layer index	Layer height, km	Level index	Level height, km
1	Surface - 0.5	1	0
2	0.5 - 1.0	2	1
3	1.0 - 1.5	3	2
4	1.5 - 2.0	4	3
5	2.0 - 2.5	5	4
6	2.5 - 3.0	6	5
7	3.0 - 3.5	7	6
8	3.5 - 4.0	8	7
9	4.0 - 5.0	9	8
10	5.0 - 6.0	10	9
11	6.0 - 8.0	11	10
12	8.0 - 10.0	12	12
13	10.0 - 14.0	13	14
14	14.0 - 18.0	14	16

total precipitation water is an important component to produce rainfall¹⁸. Convective rainfall has an approximately cubic relationship with the net heat evolved/ absorbed from the earth's surface to a height of 16 km in June (Fig. not shown), with a quadratic relationship for the same variables in October [Fig. 3(c)].

3.4 Convective rainfall vs CLW, PW and LH at various levels of the atmosphere

Some effort has been made to determine whether the intensity of convective rainfall has any relationship with the parameters (LH, PW and CLW) at individual levels in the atmosphere (Figs not shown). It was found that for the month of June, a relationship can be established between convective rainfall and LH from the surface to a height of 8 km, and that the two variables are generally related via a quadratic or cubic relationship. It may be seen that

convective rainfall has a cubic relationship with LH at peak levels of CLW during June.

For the month of October, a relationship was found to exist for LH between the surface and a height of 4 km, and this varies from level to level; in other words, at the surface, 2 km and 4 km above the surface, the relationships are quadratic, cubic and quadratic, respectively, while at 1 km and 3 km above the surface, a linear relationship is seen. The same study between convective rainfall and PW in the month of June mostly shows a cubic relationship between the surface and 2-2.5 km, above which the two quantities do not show any significant relationship.

In general, the intensity of convective rainfall has either a quadratic or a cubic relationship with CLW for each of the levels from 0.5 km to 8 km in the month of June. The relationship at the peak CLW

Table 4—Vertical profile of CLW, PW and LH at Salem in 2007

Date	Relationship			PCL*	PPW*	PLE*	PLA*
	CLW / ht	PW / ht	LH / ht				
10 Jun	y = -27.2 + 29.9 x - .01 x ² + 0.14 x ³	y = 125.95 + 24.3 x - 6.65 x ² + 0.31 x ³	Oscillatory	6, 7	3	4	1
18 Jun	y = -19.1 + 25.3 x - 3.48 x ² + 0.13 x ³	y = 49.36 + 12.9 x - 3.11 x ² + 0.14 x ³	Oscillatory	6	3	3, 4	1
22 Jun	y = -27.2 + 29.9 x - 4.01 x ² + 0.14 x ³	y = 70.83 + 13.97 x - 3.79 x ² + 0.18 x ³	Oscillatory	6, 7	3	3, 4	1
23 Jun	y = -24.4 + 28.1 x - 3.8 x ² + 0.14 x ³	y = 62.82 + 13.7 x - 3.55 x ² + 0.1 x ³	Oscillatory	6, 7	3	3, 4	1
04 Jul	y = -25.5 + 29.4 x - 3.98 x ² + 0 x ³	y = 64.63 + 13.8 x - 3.61 x ² + 0.17 x ³	Oscillatory	6	3	3	1
07 Jul	y = -19.5 + 25.4 x - 3.48 x ² + 0.13 x ³	y = 50.73 + 12.7 x - 3.09 x ² + 0.14 x ³	Oscillatory	6	3	3, 4	1
01 Aug	y = -27.4 + 33.9 x - 4.11 x ² + 0.13 x ³	y = 382.76 + 67.1 x - 17.21 x ² + 0.75 x ³	Oscillatory	6	2	8	1
23 Aug	y = -20.7 + 23.4 x - 3.13 x ² + 0.11 x ³	y = 84.99 + 9.3 x - 3.34 x ² + 0.16 x ³	Oscillatory	6, 7	2, 3	8	1
17 Sep	y = -27.3 + 30.3 x - 4.03 x ² + 0.14 x ³	y = 86.17 + 13.03 x - 3.97 x ² + 0.19 x ³	Oscillatory	6, 7	2, 3	4	1
20 Oct	y = - 57.1 + 58.4 x - 7.75 x ² + 0.28 x ³	y = 109.71 + 23.01 x - 6.09 x ² + 0.28 x ³	Oscillatory	6, 7	3	4	1
21 Oct	y = - 21.6 + 24.8 x - 3.34 x ² + 0.12 x ³	y = 75.29 + 11.4 x - 3.47 x ² + 0.16 x ³	Oscillatory	6	2, 3	8, 9	1
23 Oct	y = - 21.9 + 24.9 x - 3.37 x ² + 0.1 x ³	y = 60.45 + 13.01 x - 3.39 x ² + 0.16 x ³	Oscillatory	6	3	3, 4, 8, 9	1
24 Oct	y = - 37.1 + 39.1 x - 5.2 x ² + 0.18 x ³	y = 94.03 + 16.3 x - 4.66 x ² + 0.22 x ³	Oscillatory	6, 7	3	4	1
26 Oct	y = - 13.03 + 16.5 x - 2.24 x ² + 0.1 x ³	y = 82.467 + 5.3 x - 2.65 x ² + 0.13 x ³	Oscillatory	5	2	7,8, 9	1
27 Oct	y = - 25.2 + 29.2 x - 3.9 x ² + 0.14 x ³	y = 123.19 + 29.9 x - 7.59 x ² + 0.35 x ³	Oscillatory	6	2, 3	4,5	1
28 Oct	y = - 46.7 + 48.6 x - 6.3 x ² + 0.22 x ³	y = 143.76 + 20.8 x - 6.44 x ² + 0.30 x ³	Oscillatory	6, 7	2, 3	4	1
06 Nov	y = - 50.9 + 54.8 x - 7.38 x ² + 0.27 x ³	y = 87.04 + 19.8 x - 5.10 x ² + 0.23 x ³	Oscillatory	6	3	3	1

*Level at which peak CLW (PCL), peak PW occurs (PPW), peak latent heat evolved (PLE) and peak latent heat absorbed (PLA) occurs.

level is a cubic / quadratic. In the month of October, at the peak CLW level, CLW bears a power relationship with convective rainfall. At other levels, the relationship differs between levels.

On all the days during June-November, convective rain was found to have a power relationship with the total available CLW in the atmosphere from surface up to 18 km [Fig. 3(d)], with PW [Fig. 3(e)] and LH [Fig. 3(f)] the relationships are cubic.

3.5 Inter-relationships between CLW, PW and LH

In order to determine whether there exist any inter-relationships between CLW, PW and LH, and whether such relationships vary by month, the total CLW in the atmosphere has been plotted against the total LH for the months June-November [Fig. 4(a)], and the total LH has been plotted against the total PW [Fig. 4(b)]. It was found that both these relationships showed a cubic dependence on LH. No particular

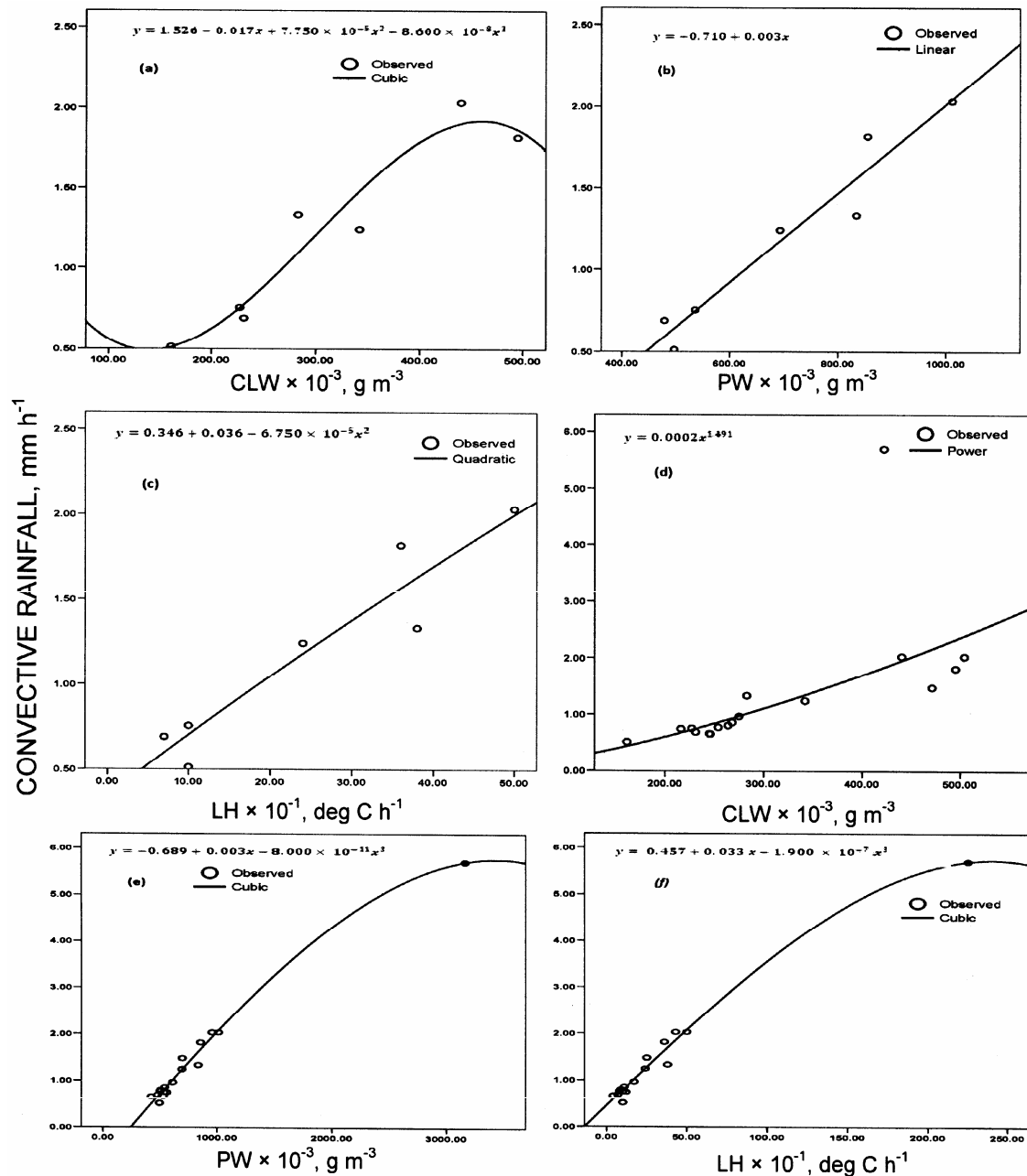


Fig. 3—Relationship between convective rainfall and meteorological parameters at Salem in 2007: (a) Convective rainfall – CLW (October); (b) Convective rainfall – PW (October); (c) Convective rainfall – LH (October); (d) Convective rainfall – CLW (June-November); (e) Convective rainfall – PW (June-November); and (f) Convective rainfall – LH (June-November)

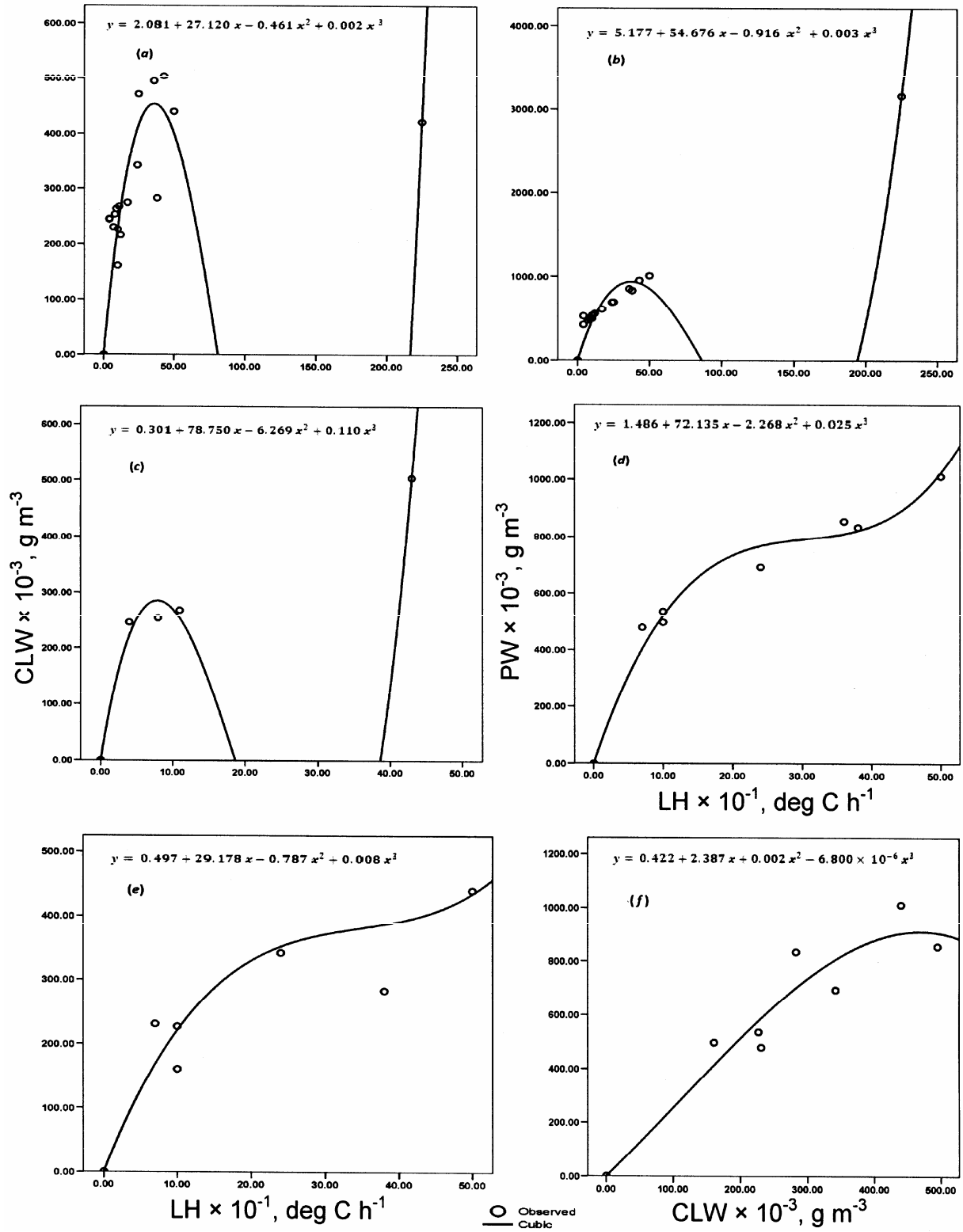


Fig. 4—Interrelationship between meteorological parameters at Salem in 2007: (a) CLW-LH (June-November); (b) PW-LH (June-November); (c) CLW-LH (June); (d) PW-LH (October); (e) CLW-LH (October); and (f) CLW-PW (October)

relationship is found to be appropriate for correlating the total CLW and the total PW when all the data for June–November are grouped together. In the month of June, the total CLW is seen to have a linear relationship with the total PW (Fig. not shown) and a cubic relationship with total LH [Fig. 4(c)].

The total PW is found to have a cubic relationship with total LH in the month of June (Fig. not shown), and in October, the relationships between total PW and total LH, total CLW and total LH, and total PW and total CLW are all cubic [Figs 4(d), 4(e) and 4(f), respectively].

4 Conclusions

The S-W monsoon brings more rainfall to Salem than the N-E. The low intensities of rainfall are the most predominant for both S-W and N-E monsoons at Salem for most years. Heavy rainfall was found to be short-lived, and low rainfall persisted for longer periods. The duration of very low rainfall was longer in N-E monsoon as compared to the S-W. Heavy and very heavy rainfall persisted longer in S-W than in N-E monsoon. It was found that El Nino mostly brought below normal rainfall over Salem, but the occurrence of less than average rainfall at Salem was not always associated with the El Nino phenomenon. Similarly, La Nina was found to bring above normal rainfall over Salem, but the occurrence of higher rainfall than normal was not always associated with La Nina events for the years studied. In fact, not all El Nino/La Nina events produce the same effect at a particular station, in view of the fact that the shape and size of different El Nino/La Nina events varies¹².

For the entire period, peak CLW was found to occur at the same height on all days. The peak PW always occur in the range of 0.5–1.5 km. The LH values show peaks at the same level in June and July, however, in other months the peaks occur at different levels on different days. Over Salem, CLW and PW always have a cubic relationship with height, irrespective of day and month. The variation of LH with height shows an oscillatory trend for the entire period. A good correlation is found to exist between convective rainfall at the earth's surface and CLW, PW and LH. The study shows that CLW, PW and LH are predictors of rainfall.

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