A study of seasonal variation of point discharge current during thunderstorms at Pune, India

G.K. Manohar¹

and

S.S. Kandalgaonkar², M.I.R. Tinmaker² and M.K. Kulkarni²

¹*Retired Scientist, Indian Institute of Tropical Meteorology, Pune – 411 008, India*

²*Indian Institute of Tropical Meteorology, Pune – 411 008, India.*

Abstract. This manuscript presents the results of measurements of the point discharge current (PDC) made during a large number of thunderstorms events at Pune (18°32'N, 73°51'E, 559 m asl) India. The PDC data are used to study various aspects of the current such as: seasonal variation, association of the current amplitude with monthly mean maximum surface air temperatures, comparison of –ve and +ve PDC ratio. The analysis of amplitudes and durations of current spells showed that longer spell durations are associated with higher current amplitudes and vice-versa. A study of monthly (March-October) variation of PDC with monthly mean maximum surface air temperatures indicated that the total behavior of PDC is similar to that of the surface air temperatures, and the correlation coefficient (R) between these two parameters is 0.924 which is significant at 0.1% level. Comparison of PDC between premonsoon and monsoon season thunderstorms suggested that the premonsoon season thunderstorms outclass the monsoon season ones by at least a factor of two in the charge transfer process to the earth. The ratio analysis of point discharge current revealed that the average value of PDC ratio over Pune region is 1.71 which further suggests the dominance of the negative PDC.

Keywords : Point discharge current, thunderstorm, electrification

1. Introduction

The phenomenon of electric discharges in the free atmosphere near ground surface from the tips of varieties of earthed conductors during thunderstorms, is termed as point discharge current (PDC). Because of direct relevance of PDC to storm electrification, initiation of lightning, and maintenance of earth's negative charge, PDC was measured and studied extensively in many study programmes during the early half of the twentieth century (Chalmers, 1967). This is evident from the large number of studies starting from the works of Wormell (1930) who first proposed PDC play an important role in the electrical balance sheet. One important result of the above studies is the characteristic dependence of PDC on the density and heights, of the discharge objects. Other significant conclusion is the space charge produced by unipolar ions near ground surface generally acts to reduce the intensity of ground electric field. After 1967, many researchers carried out considerable work on PDC (Kamra, 1969; 1989; Ette and Utah (1973a,b), Rao and Ramanadham (1979), Standler and Winn (1979), Vonnegut (1984), Asuma et al, (1988), Rahman and Saunders (1988), Engholm et al (1990), Williams and Heckman (1993), Marcz and Bencze, 1998). A common conclusion drawn by their research is : PDC might be a very important factor in the transfer of charge between the thunderstorms and the earth.

From the references cited above we note that most of the work on PDC has been done outside India except few studies [Chiplonkar (1940) and Selvam (1970)]. As time passed on, PDC measurements were continued but their objectives and locations of measurements witnessed a change (Murty et al., 1985; Manohar, 1985, 1993; Manohar et al., 1989, 1990, 1991, 1999; Kandalgaonkar, 1999; Kandalgaonkar et al., 2001). A survey of the above literature suggests that PDC has been examined for a short period although the events of its occurrence are more. Hence the present study has taken up in which the PDC data for a total of nearly 65 thunderstorm days during 7 year period (1971-1977) are analyzed and the results are presented.

2. Instrumentation and measurement site

The point-discharge element consisted of a platinum/10% iridium needle, 0.5 mm in diameter, about 2 cm long, and erected at a height of 14 m above the ground level. The measurable range of current was $\pm 5 \mu\text{A}$ which was generally detectable for a storm located ~ 15 km around the point of observations. The measurement site was located to the western sector of the city. This was ~ 4 km from the main city of Pune, and was devoid of any source of pollution or nearby chimney. The details of the measurement technique and the site are discussed elsewhere (Kandalgaonkar et al., 2001).

3. Observations and method of analysis of PDC data

The PDC (either polarity) and electric field data were recorded regularly during the thunderstorm events over the Pune region. Figure 1 represents one sample record of surface electric field and PDC on 14 May 1974. The sign convention adopted for PDC is : the current is said to be positive when the over head excess positive charge give positive potential gradient and vice-versa, since the average sign of PDC is same as the potential gradient (Chalmers, 1967; Standler and Winn 1979). Monthly distribution of thunderstorm days from 1971 to 1977 is presented in Table 1. The minute interval data of PDC of either polarity during each occurrence spell of 65 thunderstorm days forms the data set for the present study. The duration and amplitude of the current in each spell was worked out. The daily mean amplitude of the current of either polarity is obtained for each spell. The weighted average technique is used to obtain the duration. These values are further utilized to obtain monthly mean (MM) amplitude (Table 2).

Fig.1. One sample record of few spells of PDC and surface atmospheric electric potential gradient measured during thunderstorm activity on 14th May 1974 at Pune [Adopted from Manohar et al., 1999].

4. Results and Discussion

4.1 Variation of PDC amplitude with duration

Figure 2 shows the variation of average amplitude current with the time duration. In this case the total duration is divided into class interval of 10 minute each such as 0-10, 10-20..... 90-100 minutes. The current values in each class interval duration are clubbed together and the average current is calculated and it is shown against the corresponding interval. A smooth curve is drawn respectively through positive and negative data points. The two curves show the variation of average

Table 1 : Monthly number of days of thunderstorms during 1971-1977 at Pune used for PDC analysis

Months	Years							Total
	1971	1972	1973	1974	1975	1976	1977	
March			1					01
April		2	3	2				07
May		3	3	10	5		2	23
June			8			6	7	21
July				2				02
August				2				02
September	1		1					02
October			7					07
Total	01	05	23	16	05	06	09	65

Table 2 : Storm-averaged monthly (March-October) mean maximum (MMM) and monthly mean (MM) amplitude and duration of PDC during 7 year period (1971-1977) thunderstorm at Pune.

Months	Amplitude of PDC							
	Positive PDC				Negative PDC			
	MMM μ A	MM μ A	MMM-MM	Durations min	MMM μ A	MM μ A	MMM-MM	Durations min
March	0.75	0.37	0.38	39	0.92	0.60	0.32	113
April	0.93	0.54	0.39	58	1.32	0.84	0.48	65
May	0.88	0.53	0.35	57	1.02	0.62	0.40	66
June	0.73	0.35	0.38	53	0.82	0.33	0.49	87
July	0.22	0.19	0.03	21	0.53	0.25	0.28	34
August	0.27	0.15	0.12	37	0.33	0.19	0.14	19
September	0.60	0.39	0.21	47	0.72	0.32	0.40	48
October	0.35	0.29	0.06	32	0.29	0.21	0.08	24

current in relation to the length of the spell duration. This analysis has shown that there are in total 217 spells of negative current and 205 spells of positive current. Out of these negative and positive spells, 33% and 30% spells are of 1-20 minutes duration, 47% and 42% are of 21-60 minutes and 7% and 20% spells are of 61-90 minute duration and 13% and 8% are of > 90 minutes respectively. An important result of Figure 2 is that the basic trend of variation of currents of either polarity is similar. The longer spell durations are associated with higher current amplitudes and vice a versa. This behavior is more obvious and clear with negative current. This result is quite expected as the average current duration and amplitude is very much dependent on the distance from the measurement site. From this figure it is also seen that the curve for negative current well over lays the positive current. This observation appears to be quite consistent with the consideration of the positive dipole structure of a storm cloud as proposed by Wilson (1916). Interestingly, we have compared the profile of negative current with that of the electric field at the ground surface as a function of distance from the axis of a positive dipole distribution (Chapter 3, page 50, Figure 3.1 of MacGorman and Rust, 1998). This comparison of duration and amplitude variation of PDC suggests that storms that are closer to the station (~ 4 km) have longer duration and stronger current amplitude than when they are few km away. The distance scale fitted to this empirical relation in this figure indicates that for the storms, which are beyond 15 km from the point of observation, the chances of occurrence of PDC are less.

Fig. 2. Variation of average amplitude of currents of spell durations in the range 1-10, 11-20, 21-30, ----, 91-100 minutes.

4.2 Monthly (April-October) variation of PDC and surface air temperature

In many previous studies [Williams *et al.*, 1992; Williams, 1992, 1994; Jayaratne, 1993; Manohar *et al.*, 1999; Manohar and Kesarkar, 2003(a,b)] surface air temperature (monthly mean maximum dry air and wet-bulb) is used as a proxy for studying convective growth of thunderstorms, lightning flash rate and deep convection. Since PDC is one of the thunderstorm related parameter in this section the authors have examined the possible relationship of PDC with maximum surface air temperature and it is shown in Figure 3. This figure shows monthly mean maximum amplitudes of PDC, and monthly mean maximum surface air temperatures at Pune (IMD, 1999). From this figure it is seen that the maximum temperature of 41.3°C observed in April, reduces systematically by ~ 10°C in the next three months of (May-July) and attains a minimum (~30.7°C) in August. Temperature is again gradually picked up in September and becomes ~33°C in October. The corresponding profile of PDC also shows variation parallel to that of the temperature. We note that PDC attains a seasonal low value of 0.30 μA in August. It is slightly picked up in September but again falls in October. The correlation coefficient (R) between PDC and temperature is 0.924 and it is significant at 0.1% level. Thus behavior of PDC and temperature suggests that PDC participates in cloud electrification where the surface air temperature is very high.

4.3 Seasonal variation of PDC during premonsoon and monsoon seasons

The major period of the annual thunderstorm activity around Pune region is during March-October months. These eight months mainly cover the premonsoon (March-May) and the southwest monsoon (June-September) seasons of the annual period of major convective activity. Thunderstorm activity during the remaining four months (January-February and November-December) is almost negligible (Manohar *et al.*, 1999). Since these two seasons follow each other and form an annually repetitive cycle of events of thunderstorms, a comparison of PDC activity during these two seasons is considered meaningful and important.

Table 2 gives the storm averaged monthly mean maximum (MMM) and monthly mean (MM) amplitude and duration of PDC of either polarity during thunderstorms at Pune. The months considered here are from March to October. The columns 4 and 8 of this table give the difference between (MMM) and (MM) for positive and negative PDC respectively. From this table we note that

Fig. 3. Seasonal variation of monthly mean maximum surface air temperatures (°C) and PDC (μA) during thunderstorms at Pune.

the differences in the four months of the summer season (March-June) are considerably large for positive and negative PDC. In monsoon season these differences are reduced and were minimum in July for positive PDC and in August for negative PDC. The magnitude of PDC in October is nearly identical for either polarity. Thus, this comparison brings out the difference in cloud electrification of continental and maritime cloud systems. This observed feature of higher and lower values of PDC in the premonsoon and monsoon season appears to be the result of extreme and subdued electrification of the respective season. This result is in agreement with the earlier studies (Manohar and Kandalgaonkar, 1995; Manohar *et al.*, 1999). In some other study Manohar and Kesarkar 2005 have shown that about 60% of the thunderstorm activity over the Indian region takes place in the monsoon season and ~40% activity is restricted to the 3 months of the premonsoon season. The analysis showed that PDC contribution from large number of less electrified monsoonal thunderstorm is not comparable with the strongly electrified premonsoon storm. This contribution is maximum in March-May months. Thus the seasonal analysis of PDC suggested that the premonsoon season thunderstorms outclass the monsoon season by at least a factor of two in the charge transfer process to the earth.

4.4 Comparison of point discharge ratio (Q_- / Q_+)

Amongst conduction current, precipitation current, lightning and PDC, which contribute to the transfer of charge to the earth, PDC plays an outstanding role since its single contribution to the charge transfer is markedly higher than those of the rest (Wormell, 1930; Chalmers, 1967; Williams and Heckman, 1993; MacGorman and Rust, 1998). The sign of the charge transferred by PDC could be both, positive and negative. Therefore, an understanding of the polarity dominance may be essential requirement for the maintenance of earth's negative charge. Many researchers worked on the polarity dominance of PDC and the results are given available elsewhere (Chalmers, 1967; Kamra, 1968; Rao and Ramanadham, 1979; Ette and Oladiran, 1980). The common results of these studies indicated that this ratio is different for different locations and it is greater in tropical and subtropical region than in temperate one's. The detailed explanation for variation of PDC ratio is discussed in Brook *et al.*, 1982. Since the PDC data in the present study is for substantial period the authors have taken the opportunity to calculate the ratio of Q_- / Q_+ with the available data and compared it with others (Table 4). Table 3 illustrates a frame of monthly mean amplitude (March-October) of currents and their durations averaged per storm per month at Pune. This data are used to obtain, negative and positive charge

received by the earth during March-October months and it is shown in columns 6 and 7 of the table. The last column of this table gives the ratio values from March-October. From this table it is seen that the PDC ratio is highest for the month of March and lowest in the October. From the month of March the PDC ratio decreases till May and again increases in June and become maximum in July. This increase in PDC ratio in June and July is associated with the onset phase of monsoon and prevailing break monsoon situation in the month of July (Manohar et al., 1999). The highest value of PDC ratio in the month of March is due to the frequent occurrence of thunderstorms, which are due to higher convective activity due to intense solar heating (MacGorman and Rust, 1998). The value of PDC ratio noticed in September is slightly higher than the August and October which is again linked with the withdrawal phases of the monsoon and the thunderstorm associated with the western disturbances (Manohar et al., 1999). From this table it is also seen that the average value of ratio over the Pune region is 1.71. This value is seen to be consistent with the values reported elsewhere (Table 4). The ratio values obtained in this study and the values reported in Table 4 by other authors, thus show the dominance of the negative PDC over the regions under the study. Since the PDC ratio shows month-to-month variation during the period of study, it is interesting to examine the ratio in different seasons. With this view in the following section the seasonal analysis of point discharge ratio is discussed.

From Table 3 it is seen that the total negative / positive charge received by the earth through a single discharge needle is $\sim -13.47 / 7.90$ respectively. To obtain the net charge transferred to the Earth by the PDC process the climatological normal values published by IMD (IMD, 1967, 1999) for number of thunderstorm days from March till October at Pune are used and these values are : 1.5, 4.0, 5.0, 3.0, 0.3, 0.9, 4.0, 5.0; and 1.6, 4.1, 6.1, 4.0, 0.7, 0.9, 5.3 respectively. It is noted that the net-

Table 3 : Storm-averaged monthly (March-October) mean amplitude (MM) and duration of point discharge current (PDC) and derived values of charge received by the earth during 7 year period (1971-1977) thunderstorm at Pune.

Months	Negative PDC μA_-	Positive PDC μA_+	Duration of Negative PDC Minutes	Duration of Positive PDC Minutes	Negative charge (Q_-) received by earth (mC.)	Positive charge (Q_+) received by earth (mC.)	Point discharge ratio : Q_- / Q_+
March	0.60 (0.40)	0.37 (0.25)	113 (30)	39 (10)	4.07	0.87	4.68
April	0.84 (0.55)	0.54 (0.40)	65 (23)	58 (37)	3.28	1.88	1.74
May	0.62 (0.45)	0.53 (0.40)	66 (37)	57 (40)	2.45	1.81	1.35
June	0.33 (0.34)	0.35 (0.35)	87 (119)	53 (41)	1.72	1.11	1.55
July	0.25 (0.09)	0.19 (0.05)	34 (9)	21 (4)	0.51	0.24	2.12
August	0.19 (0.10)	0.15 (0.08)	19 (0)	37 (20)	0.22	0.33	0.67
September	0.32 (0.23)	0.39 (0.31)	48 (17)	47 (8)	0.92	1.10	0.84
October	0.21 (0.13)	0.29 (0.25)	24 (21)	32 (27)	0.30	0.56	0.53

Figures in bracket denote standard deviation : $\Sigma Q_- = 13.47$; $\Sigma Q_+ = 7.90$; $\Sigma Q_- / \Sigma Q_+ = 1.71$

Table 4 : A summary of point discharge ratio (Q_- / Q_+) during disturbed weather situations at various geographic locations of the world.

Observer	Place	Ratio of -ve to +ve	Duration
Wormell (1927, 1930)	Cambridge(England)	2.0	3 years
Whipple and Scarse (1936)	Kew (England)	1.7	2 years
Immelmann (1938)	Pretoria (S. Africa)	2.8	2 years
Yokouti (1939)	Japan	2.1	1 year
Gerashimova (1939)	Elbrus (Caucasus)	1.6	14 years
Chiplonkar (1940)	Colaba (India)	2.9	1 year
Perry, Webster and Baguley (1942)	Nigeria	2.9	9 months
Lutz (1944)	Munich (Germany)	2.0	3 years
Chalmers and Little (1947)	Durham (England)	1.4	8 months
Allsopp (1952)	South Africa	2.2	
Michnowski (1957)	Poland	1.5	6 storms
Sivaramkrishnan (1957)	Poona (India)	2.0	1 year
Kamra (1968)	Roorkee (India)	1.3 for all foul weather 2.5 for all foul weather including dust storms	1 year (May 1966-April 1967)
Ette and Oladiran (1980)	Nigeria (Africa)	2.1) All foul weather 1.9) occasions 1.9) of 4 years	1974, 1975, 1976, 1977
Manohar et al., (1990)	Poona (India)	0.6))) Seasonal ratio for) thunder- 1.3) storms))	10 thunder-storms during May-June of 1987 11 thunder-storm during April-June of 1988
Marcz and Bencze (1998)	Nagycekn (Hungary)	0.7 to 1.3	All weather during 1961-1996
Rao and Ramanadham (1979)	Visakhapatnam (India)	1.8 for all foul weather 2.4 for only thunderstorms	Two years 1973, 1974

First twelve values adopted from Chalmers (1967)

charge transferred to the earth considering the 1967 and 1999 climatological normals comes out as -13.4 mC and -15.3 mC respectively for the months of March-October through single discharge needle. Thus the net negative charge received by the earth in the present study is in agreement with values obtained by using the climatological normals and the values reported elsewhere [Chiplonkar

(1940); Rao and Ramanadham (1979); Kamra (1968) and by Manohar (1993) at Bombay, Vishakhapatnam, Roorkee and Pune respectively are -20.0, -9.6 and -13.0, -21.4, -12.4 and -5.7 mC]. The values of -12.4 and -5.7 mC by Manohar (1993) represent just two premonsoon season thunderstorms of the years 1987 and 1988 at Pune. Thus the values obtained in the present study appear to be consistent with earlier studies.

By making two possible assumptions (Rao and Ramanadham, 1979; Kamra, 1989) namely (i) that the separation distance between trees in this area is around 10 m and (ii) that the discharge efficiency of trees and metal points is the same, we note that the amount of net annual charge transferred over an area of 1 km² by thunderstorms comes as -134 and -153 Coulomb respectively as per the earlier (1967) and revised (1999) climatological normals of monthly number of thunderstorm days. We note that this value is well within the range of values (-30 to -180) reported in the literature. Whipple and Scrase, 1936; Chalmers, 1967 showed that point discharge current transfer more negative current than positive by a factor of 1.5-3.0. Thus it may be deduced from the above analysis and the studies reported elsewhere the contribution of PDC to the negative charging of the earth is significant.

5. Conclusions

Large amount of high-resolution data from surface recordings of point discharge current (PDC) from 65 thunderstorm days at Pune has been analysed to understand : association between duration and amplitude of PDC, seasonal relationship of PDC with monthly mean maximum surface air temperatures, comparison of point discharge ratio (Q_- / Q_+) at different geographic locations, comparison of PDC between premonsoon and monsoon seasons. The results of the study show the following :

- (i) The analysis of amplitudes and durations of current spells showed that longer spell durations are associated with higher current amplitudes and vice-versa.
- (ii) A study of monthly (March-October) variation of PDC with monthly mean maximum surface air temperatures indicated that the total behavior of PDC is similar to that of the surface air temperatures, and the correlation coefficient (R) between these two parameters is 0.924 which is significant at 0.1% level.
- (iii) Comparison of PDC between premonsoon and monsoon season thunderstorms suggested that the premonsoon season thunderstorms outclass the monsoon season ones by at least a factor of two in the charge transfer process to the earth.
- (iv) The ratio analysis of PDC revealed that the average value of PDC ratio over Pune region is 1.71 which further suggests the dominance of the negative PDC.

Acknowledgements. The authors are thankful to Professor B.N. Goswami, Director and Head, Physical Meteorology and Aerology Division, IITM, Pune for their kind permission to process the work of this study from IITM.

References

- Asuma, Y., Kikuchi, K., Tanaguchi, T. and Fuji, S., Vertical structures of the atmospheric electrical potential gradient and the behavior of the precipitation charges during snowfalls near the ground surface, *J. Met. Soc. Japan*, **66**, 473-488, 1988.
- Brook, M., Nakano, M., Krehbiel, P. and Takeuti, T., The electrical structure of the Hokoriku thunderstorms, *J. Geophys. Res.*, **87**, 1207-1215, 1982.
- Chalmers, J.A., *Atmospheric Electricity*, Chapter 9 : Point Discharge Current, pp. 246, 1967.
- Chiplonkar, M.W., Measurement of point discharge current during disturbed weather at Colaba. *Proc. Indian Acad. Sci. A*, **12**, 50-54, 1940.
- Engholm, C.D., Williams, E.R. and Dole, R.M., Meteorological and electrical conditions associated with positive cloud to ground lightning, *Mon. Wea. Rev.*, **118**, 470-487, 1990.
- Ette, A.I. and Utah, E.U., Measurement of point-discharge current density in the atmosphere, *J. of Atmos. and Terr. Phys.*, **35**, 785-793, 1973a.

- Ette, A.I. and Utah, E.U., Studies of point discharge characteristics in the atmosphere, *J. Atmos. Terr. Phys.*, **35**, 1799-1809, 1973b.
- Ette, A.I. and Oladiran, E.O., The characteristics of rain electricity in Nigeria, I – Magnitude and variations, *Pageoph*, **118**, 753-764, 1980.
- IMD (1967), Climatological Normals, Tables of Observations in India, IMD.
- IMD (1969), Climatological Normals, Tables of Observations in India, IMD.
- Jayarathne, E.R., Conditional instability and lightning incidence in Gaborone, Botswana, *Meteorol. Atmos. Phys.*, **52**, 169-175, 1993.
- Kamra, A.K., Charge transfer in the atmosphere by point discharge current, *J. Geomag. Geoelec.*, **20**, 111-113, 1968.
- Kamra, A.K., Effect of wind on diurnal and seasonal variations of atmospheric electric field, *J. Atmos. Terr. Phys.*, **31**, 1281-1286, 1969.
- Kamra, A.K., Charge transfer by point discharge below dust storms. *Geophys. Res. Lett.*, **16**, 127-129, 1989.
- Kandalgaonkar, S.S., Ph.D. Thesis, Some studies of atmospheric electrical parameters : Fair and Disturbed weather conditions”, University of Pune, Pune, 1999.
- Kandalgaonkar, S.S., Kulkarni, M.K. and Tinmaker, M.I.R., Time evolution and frequency distribution of point discharge current, *J. Atmos. Electricity of Japan*, **21**, 2, 95-100, 2001.
- MacGorman, D.R. and Rust, W.D., The Electrical Nature of Storms, Oxford University Press, p. 50, 1998.
- Manohar, G.K., A case study of surface atmospheric electric field, point discharge current, wind and air temperature near a thermal power plant, *Indian J. of Power and River Valley Development*, **12**, 207-213, 1985.
- Manohar, G.K., Kandalgaonkar, S.S. and Sholapurkar, S.M., Effects of thermal power plant emissions on atmospheric electric parameters, *Atmos. Environ.*, **23**, 843-850, 1989.
- Manohar, G.K., Kandalgaonkar, S.S. and Sholapurkar, S.M., Some characteristics of point discharge current during to premonsoon season thunderstorms at Pune, *Current Science*, **99**, 367-370, 1990.
- Manohar, G.K., Kandalgaonkar, S.S. and Sholapurkar, S.M., Point discharge current observations in the thunderstorm environment of the years 1987 and 1988 at Pune, *Mon. Wea. Rev.*, **119**, 3104-3107, 1991.
- Manohar, G.K., Some studies of surface atmospheric electricity parameters in different environments over Indian region, Ph.D. Thesis, University of Pune, Pune, 1993.
- Manohar, G.K. and Kandalgaonkar, S.S., Estimation of electrical charges deposited to the ground by lightning in thunderstorms at Pune, *Ind. J. Radio and Space Phys.*, **24**, 297-307, 1995.
- Manohar, G.K., Kandalgaonkar, S.S. and Tinmaker, M.I.R., Thunderstorm activity over India and the Indian southwest monsoon, *J. Geophys. Res.*, **104**, D4, 4169-4188, 1999.
- Manohar, G.K. and Kesarkar, A.P., Climatology of thunderstorm activity over the Indian region : I, A study of East-west contrast, *Mausam*, **54**, 4, 819-829, 2003a.
- Manohar, G.K. and A.P. Kesarkar, Climatology of thunderstorm activity over the Indian region : A study of east-west contrast, *Proc. Of International Conference on Atmospheric Electricity, France*, 2003b.
- Manohar, G.K. and Kesarkar, A.P., Climatology of thunderstorm activity over the Indian region : III. Latitudinal and seasonal variation, *Mausam*, **56**, 3, 581-592, 2005.
- Marcz, F. and Beneze, P., Surplus of negative charge flow in point-discharge current as shown by variations on different time scales at Nagycenk station, *J. Atmos. Solar and Terr. Phys.*, **60**, 1435-1443, 1998.
- Murty, A.S.R., Selvam, A.M., Manohar, G.K., Devara, P.C.S., Raj, P.E., Kandalgaonkar, S.S. and Ramana Murty, Bh.V., Warm cloud electrical and microphysical responses to salt seeding, *Proc. IV Scientific Conference on Weather Modification*, 12-14 August 1985, 493-496.
- Rahman, M.K. and Saunders, C.P.R., Corona from splashing water drops, *J. of Atmos. & Terr. Physics*, **50**, 545-555, 1988.
- Rao, A.M. and Ramanadham, R., Study of transfer of charge by point discharge in the atmosphere, *PAGEOPH*, **117**, 904-912, 1979.

- Selvam, A.M., On the measurement of surface atmospheric electrical potential gradient and point discharge current using electronic methods. I.M.D. Sci. Report No. 121, 1-6, 1970.
- Sivaramkrishnan, M.V., Point discharge current and the earth's electric field and rain charge during disturbed weather at Poona, *Ind. J. Meteorol. Geophys.*, **8**, 379-390, 1957.
- Standler, R.B. and W.P. Winn, Effects of corona on electric fields beneath thunderstorms, *Quart. J. Roy. Met. Soc.*, **105**, 285-302, 1979.
- Vonnegut, B., Reduction of thunderstorm electric field intensity produced by coronas from a nearby object, *J. Geophys. Res.*, **89**, 1468-1470, 1984.
- Whipple, F.J.W., and Scrase, F.J., Point-discharge in the electric field of the Earth. *Geophys. Mem. VII.*, No. 68, 1-20, 1936.
- Williams, E.R., Rutledge, S.A., Geotis, S.G., Renno, N., Rasmussen, E. and Rickenbach, T., A radar and electrical study of tropical 'Hot Towers', *J. Atmos. Sci.*, **49**, 1386-1395, 1992.
- Williams, E.R., The Schuman Resonance : A global tropical thermometer, *Science*, **256**, 1184-1187, 1992.
- Williams, E.R. and Heckman, S.J., The local diurnal variation of cloud electrification and the global diurnal variation of negative charge on the earth, *J. Geophys. Res.*, **98**, 5221-5234, 1993.
- Williams, E.R., Global circuit response to seasonal variation in global surface air temperature, *Mon. Wea. Rev.*, **122**, 1917-1929, 1994.
- Wilson, C.T.R., On some determinations of sign and magnitude of electric discharges in lightning flashes, *Proc. Roy. Soc. A*, **92**, 555-574, 1916.
- Wormell, T.W., Vertical electric currents below thunderstorms and showers. *Proc. Roy. Soc. A*, **127**, 567-590, 1930.

(Received October 16, 2006; revised March 15, 2007;
accepted December 25, 2007)