Journal of Atmospheric and Solar–Terrestrial Physics 211 (2020) 105452

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

Atmospheric electric field variations during fair weather and thunderstorms at different altitudes

Hripsime Mkrtchyan [a,*], Gayane Karapetyan [a], Davit Aslanyan [a]

[a] *A.Alikhanyan National Science Laboratory, Armenia*

ARTICLE INFO

Keywords:
Thunderstorm activity
Fair weather
Lightning activity
Temperature
Wind speed

ABSTRACT

Ground-based electric field measurements during fair weather and thunderstorms are key parameters for Global Electric Circuit investigations and climate change assessment. We study the variations of near surface electric field during fair weather and thunderstorms. In this work we present daily, monthly and yearly distribution of thunderstorm activity from 2012 to 2019 at different research stations of Cosmic Ray Division (CRD) of the A. Alikhanyan National Science Laboratory (Yerevan Physics Institute) which has been done the first time for mentioned locations. The distribution of fair-weather days based on electric field variation and meteorological parameters are also discussed. According to results, thunderstorm activity is very high from May to June and the most active part during the day is from 15:00 to 20:00 LT at three different altitudes.

1. Introduction

Fair weather investigations show that a typical near surface electric field at the ground is between 100 and 300 V/m Marshall et al. (1999). However, at the NASA Kennedy Space Center (at sea level) and U.S. Air Force Cape Canaveral Air Station the electric field at the ground sometimes reached 400–1200 V/m shortly after sunrise on days that otherwise seemed to be fair weather. Marshal T.C. et al. (1999) investigated this phenomenon and concluded that it is caused by solar heating after sunrise. Similar phenomenon was observed in mountainous regions of Armenia and Israel. Yaniv et al. (2017) suggested that as the sun rises charged particles accumulated near the surface due to the electrode effect rise up with evaporating dew and get blown uphill by intensified surface winds. Yaniv et al. (2017), concluded that the main reason for the electric field addition in the early morning are not charged particles themselves but the addition of aerosol concentrations (that also get carried by uphill winds), which results in lower conductivity.

Past investigations have also revealed that thunderstorm activity is related to the fair weather through global electric circuits (Williams, 2009). Continuous measurements of electric fields have proven that there is not only an annual but also a daily variation of thunderstorm activity. Past investigations (Turman and Edgar, 1982, Whipple, 1929) have shown that thunderstorm activity by universal time has three maximums during each 24-h period, which correspond to the three tropical thunderstorm regions: Asia (at 09:00 UT), Africa (at 14:00 UT) and South America (at 20:00 UT) and a minimum (near 03:00 UT). It was suggested that each peak in the late afternoon hours (LT) is a result of solar heating of the surface during the day. The minimum is observed, when the sun is over the Pacific Ocean.

Ranalkar and Chaudhari (2019) discovered that May has the maximum frequency of lightning flashes and thunderstorm activity over the Indian subcontinent for 0–35N, 60E–100E. In the same work they also observed that thunderstorm activity during May occurs late at night and early in the morning hours (LT). Kumar, (2017) observed a good correlation of lightning activity with surface temperature and convective available potential energy (CAPE).

The main goal of this work is to investigate electric field variations during fair weather and thunderstorms over different regions in Armenia during the year. Data obtained from our 4 stations (Dilijan station was only used for fair weather investigations, while Nor Amberd, Yerevan and Aragats stations for both fair weather and thunderstorm activity studies). In different locations are giving excellent opportunities to investigate daily and seasonal near surface electric field disturbances, fluctuations of thunderstorms, and the relation of fluctuations with altitude. Moreover, studies of simultaneous measurements of electric field and meteorological parameters correlations can reveal thundercloud electric structure, global and local electric circuit characteristics. Thunderstorm activity investigations can also be informative to farmers and provide data for crop protection.

In this work we have taken Local Time which corresponds to UT +4

* Corresponding author.
E-mail address: hripsime@yerphi.am (H. Mkrtchyan).

https://doi.org/10.1016/j.jastp.2020.105452
Received 26 March 2020; Received in revised form 5 September 2020; Accepted 8 September 2020
Available online 10 October 2020
1364-6826/

h.

1.1. Facilities at research stations

Research stations of the Cosmic Ray Division (CRD) of the A. Alikhanyan National Science Laboratory (Yerevan Physics Institute) have been operating since last century. Stations contain various particle detectors for measuring neutral and charged fluxes of secondary cosmic rays, weather stations, sensors of electric and magnetic fields, detectors of broadband radio emission and lightning detectors. All facilities are operating 24 h a day. The accumulated data is available in an online visualization program called ADEI (Chilingaryan et al., 2010) (see http://crd.yerphi.am/ADEI).

The electric fields which accompany thunderstorms normally measure in the thousands of Volts per meter, which can be registered at ground based devices. For this study near surface electric field and the distance to lightning are measured by Boltek EFM-100 (see http://www.boltek.com/). The measurement range of the electric field is in V/m and sampling rate is 20 Hz. As it was mentioned in Mkrtchyan, (2018) Boltek EFM-100's measurement accuracy is 5%. Four Boltek EFM-100 mills are installed at Aragats research station. Another five Boltek EFM 100s operate at Nor Amberd, Yerevan, Dilijan, Sevan and Shushi stations.

For meteorological measurements Vantage Pro2 has been used, which is a customizable and extremely flexible station with a wide range of options and sensors (a rain collector, temperature and humidity sensors, anemometer, UV and solar radiation sensors) for measuring, monitoring, and managing weather data.[1] It provides measurements of more than 30 parameters every second. Parameters of interest in this study were the wind speed, wind direction, outside temperature and humidity, and pressure. The rugged components of the anemometer can record wind speeds as low as 0.3 m/s and have been tunnel-tested to withstand up to 90 m/s wind. The temperature and humidity sensors provide an outside temperature reading form −40 °C to 65 °C and a relative humidity from 1 to 100%. To measure outside pressure the station uses outside air temperature, outside humidity, elevation and atmospheric pressure data.

2. Results and discussion

2.1. Electric field during fair weather

The Earth's atmospheric electric field measurements during fair weather demonstrate that there are global and local average daily variations. The global daily variation follows the Universal Time and is typical to the geographic region of measurements taken. The local variation, on the contrary, depends on the location and time the measurements were taken.

Information on daily variability based on electric field data from several sites was investigated in Nicoll et al., (2019). Averages are hourly mean values taken from 1-min potential gradient (PG) data. There was shown clear similarity between the heavily averaged Carnegie curve and the daily averages across the GLOCAEM sites (Nicoll et al., 2019), especially during the maximum. Curves possessing a similar shape to the Carnegie curve, with a minimum in the early morning hours and single maximum around 19 UT, were observable on ~25% of days in 2016 using this averaging method. This therefore demonstrates that averaging across multiple sites may well improve the statistics of observing Carnegie-like signals on a day-to-day basis.

To study the local diurnal variation, we have made observations at 4 research stations in Armenia for data collected from 2012 to 2019. Sevan and Shushi stations were excluded from the analysis because they were installed recently and we do not have enough statistics.

Fair weather days have been selected based on meteorological data and on the E-field records. As a fair weather we have taken the near surface electric field in the range from +0.01 to +0.99 kV/m and the wind speed is less than 6 m/s. These criteria were described in (Torreson et al., 1946). We have also taken into account that any small time frame the temperature does not have severe disturbances. To analyze fair weather and thunderstorm activity, we have developed a python script and proceeded data from 2012 to 2019. Based on the described criteria and developed a python script 558 fair weather days were selected at Aragats research station, 539 at Nor Amberd, 23 at Yerevan, and 213 at Dilijan.

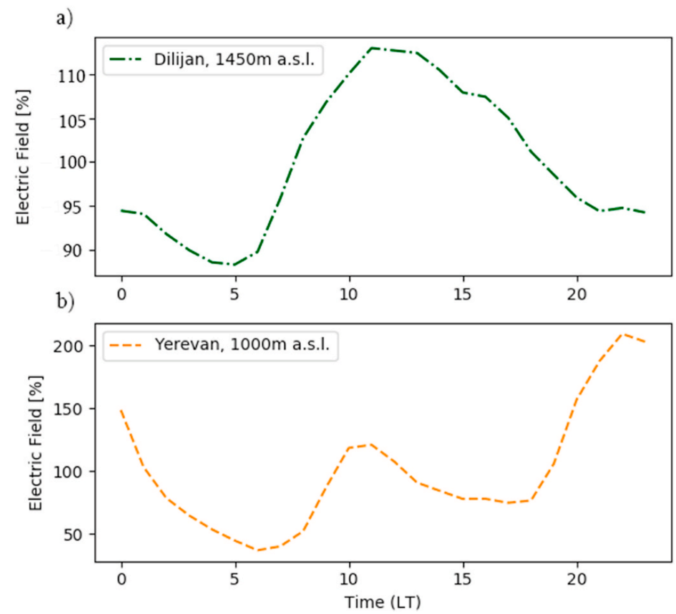

Fig. 1. Diurnal variation of Near Surface Electric Field at Dilijan(a) and Yerevan(b) research stations.

At Nor Amberd and Aragats research stations the near surface electric field in the early morning hours exhibits enhancements, which are attributed to the "Austausch" effect and well presented in Yaniv et al. (2017). In our current work Fig. 1 shows the diurnal variation of near surface electric fields for Dilijan (a) and Yerevan (b) stations in percent (%), which was calculated around the daily average electric field. Time is presented on the horizontal axis, and near surface electric field measurements relative to the average daily mean from 2012 to 2018 are presented on the vertical axis.

The first peak in Yerevan fair weather electric field curve (Yerevan curve) was observed at 11:00LT. Comparing with findings in Yaniv R. et al. (2017), we believe it can be associated with the "Austausch" effect. Although Yerevan is elevated 1000 m above sea level and located inside the city, where the pollution is very high, it is one of the lowest points in its surroundings, so the first peak can also have different origin along with the mentioned. As it was discussed in Nicoll et al., (2019), where stations with similar behavior, the early morning peak can also originate from traffic or industrial pollution. These pollutants have more influence in early morning hours possibly due to the low altitude of the planetary boundary layer. The second peak in Yerevan curve reached its maximum around 22:00 LT which is consistent with the Carnegie Curve.

Investigations of near surface electric field measurements at Dilijan research station led to an interesting finding (Fig. 2): although near surface electric field diurnal variation is similar to that of our other stations and wind speed and temperature do not have big disturbances and suggest that the weather is fair, the fair-weather electric field has negative values between −1 and 0 kV/m. At Dilijan research station we have observed an addition to the electric field in the early morning hours. As a result, the near surface electric field reaches its maximum at around 13:00 LT, which can be connected to aerosols and electrode

[1] http://www.davis.com/Assets/MoreInfo/86403-13Specs.pdf.

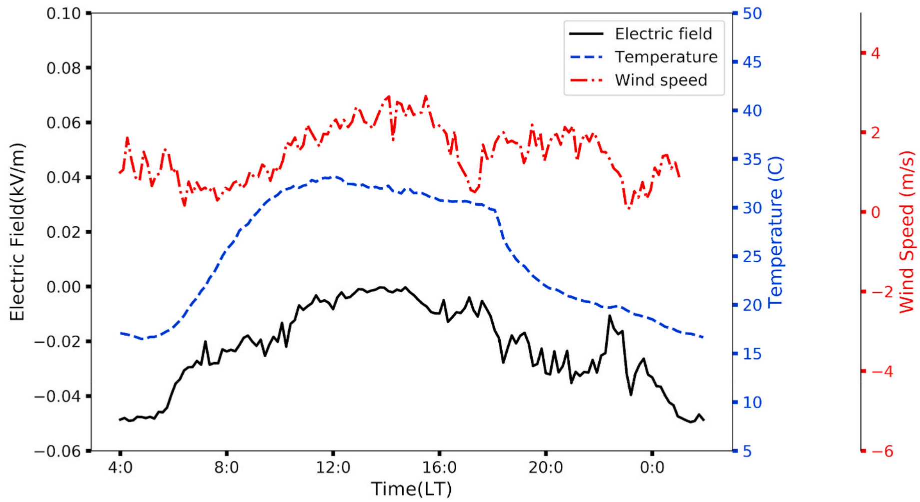

Fig. 2. A fair weather day at Dilijan station on July 4, 2018: wind speed (red curve), temperature (blue curve) and electric field (black curve).

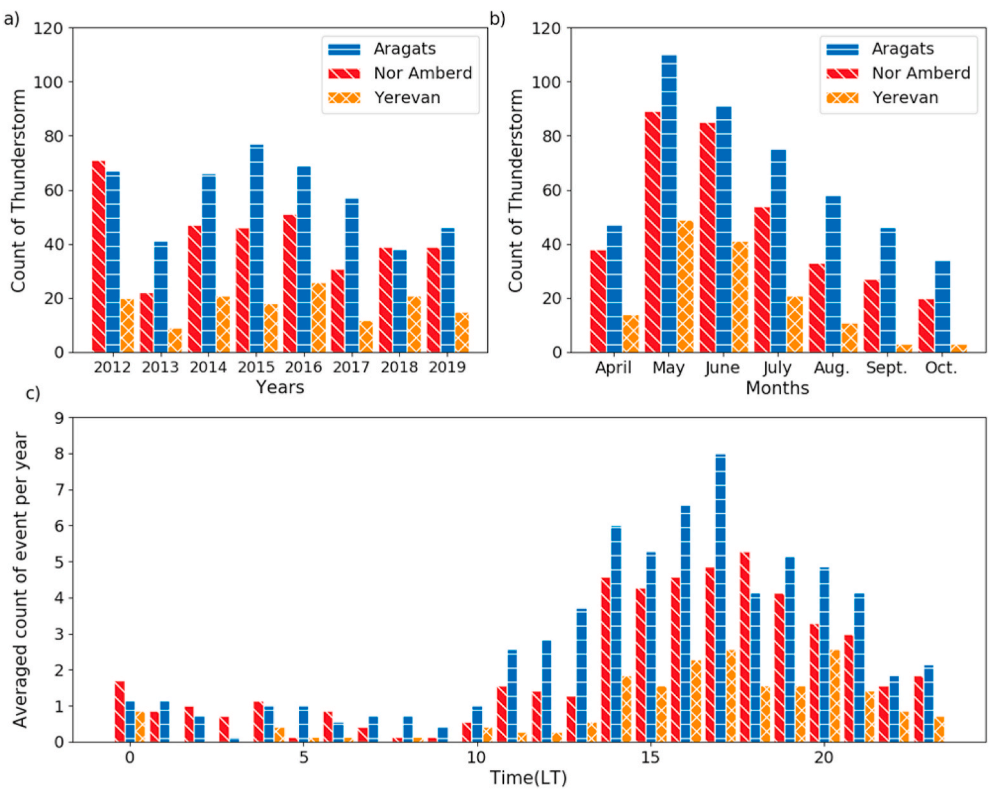

Fig. 3. Average thunderstorm yearly (a), monthly(b) and daily activity(c), data has taken from 2012 to 2019.

effect but negative values registered at this station didn't give confidence to claim it.

We will address this open question in our further studies.

2.2. Thunderstorms activity over aragats, Nor Amberd and Yerevan

The near surface electric field is registered at three stations for more than 8 years. As the thunderstorm activity is very high at Mt. Aragats and its surroundings, analyzing near surface electric field disturbances is particularly interesting. Here we present the analysis of daily, monthly and yearly thunderstorm distribution for 2012–2019 based on electric field variation during thunderstorms (see Fig. 3 a, b, c).

Fig. 3 proves the above-mentioned assumption that thunderstorm activity is high at Aragats station, which has the highest elevation. Activity at Yerevan station seems to have periodic shape and low rate comparing other stations (Fig. 3a).

According to the yearly thunderstorms distribution there is a decrease observed in 2013 at all three stations. And in 2015 when we had an active year, when storms were 1.5 times more at Aragats station compared to the average of 8 years. Compared with temperature distribution we noticed that it also has decreased in 2013. However, for this stage we didn't find any explanation for those parameters. Annual distribution of the storms is showing also possible decrease in upcoming years.

From 2012 to 2019 the monthly thunderstorm distributions at all stations are shown at Fig. 3 b. More thunderstorms are recorded from

Table 1
Coordinates of the Armenian research stations.

Name of the Station	Coordinates	Altitude above sea level(m)	Distance from Yerevan (km)
Aragats	40.47N, 44.18E	3200	39
Nor Amberd	40.37N, 44.26E	2000	26.5
Yerevan	40.205N, 44.486E	1090	–
Dilijan	40.73N, 44.83E	1300	67
Sevan	40.619N, 45.028E	1910	65
Shushi	39.75N,46.75E	1080	200

May to July with the highest peak observed in May and less afterwards. The average number of thunderstorms registered during May is 110 at Aragats, 88 at Nor Amberd and almost 49 at Yerevan (Fig. 3 b). However, at Aragats station we observed the smallest activity in October (around 34 storms).

At all three stations the investigations of daily thunderstorm distribution show that thunderstorms occur mostly between 15:00 and 20:00 LT (see Fig. 3 c), which coincides with Asian and African thunderstorm activity. Stations locations are near and the results are almost the same (see Table 1).

Table 2 shows averaged durations and count of the lightning strikes over three stations. The monthly distribution of thunderstorm durations from April to October is calculated as the mean timespan between the start and the end of a thunderstorm (see Table 2, the first block from 3rd to 5th rows). According to our investigations during thunderstorms the variations of electric field had absolute amplitude exceeding 5 kV/m and at least one lightning strike was observed. Therefore, for choosing thunderstorms we have taken those mentioned 2 criteria: the absolute value of the electric field is larger than 5 kV/m and more than 1 lightning have been registered based on Boltek EFM data. As the start (the end) of the storm was defined the time when the field is adopting higher value than 1 kV/m (after storm becoming near to fair weather). We have also noticed that in winter because of snow accumulation the electric field mill gives inconsistent fair weather electric field measurements, so in this work we investigate data for April–October. Excluding months from November to March from the research was also because of the very low frequency of thunderstorms.

Our studies show that on average the longest lasting thunderstorms observed at Aragats and Nor Amberd research stations were registered in June and lasted approximately 163 and 160 min respectively, while at Yerevan station they were registered in September and lasted approximately 203 min. As you can see from Table 2, in all three stations shortest lasting thunderstorms were observed in October.

The average monthly counts of lightning strikes from 2012 to 2019 are depicted in the second block (from 6th to 8th) of rows. According to electric field measurements by Boltek EFM-100 steep changes in electric field records, which recover in the following few hundred milliseconds indicate lightning (see Mkrtchyan H. 2018). Looking at the monthly distributions of storms we have seen that at Aragats station the highest lightning activity is recorded in June (1895 lightning strikes), however at other stations is observed the highest lightning activity in May, where we registered total 1667 (Nor Amberd) and 273 (Yerevan) lightning strikes. If we look at the yearly distribution of the lightning records, at Nor Amberd station 1350 strikes registered in 2012, making that year the most active, while during the same year, there were registered 728 and 145 strikes correspondingly at Aragats and Yerevan stations.

For Aragats and Yerevan stations uppermost activity recorded in 2016 (1040 strikes) and in 2018 (334 strikes) respectively.

Table 2
Characteristic parameters of Thunderstorms.

	Stations	From 2012 to 2019						
		April	May	June	July	August	September	October
Thunderstorm averaged duration (minutes)	Aragats	120	139	163	143	146	129	117
	Nor Amberd	146	137	159	140	133	124	117
	Yerevan	156	138	148	113	141	203	80
Count of lightning strikes	Aragats	889	1698	1895	1336	712	575	314
	Nor Amberd	402	1667	1177	747	435	355	165
	Yerevan	90	273	242	61	76	69	7

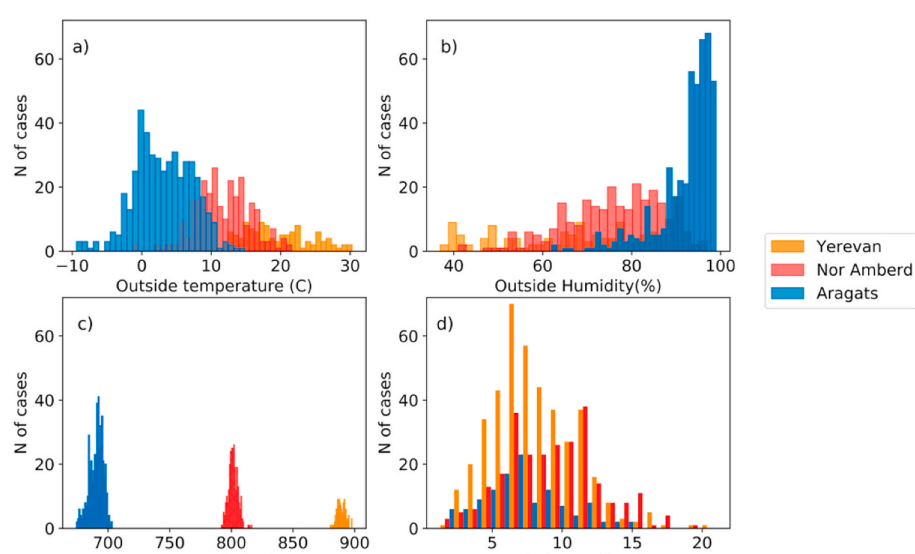

Fig. 4. Distribution of meteorological parameters during thunderstorms.

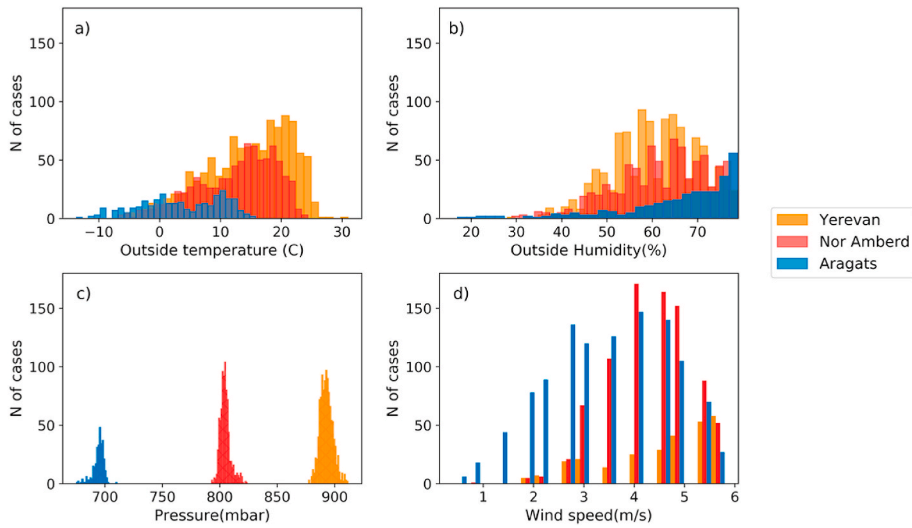

Fig. 5. Distribution of meteorological parameters during fair weather.

Table 3
Average temperature during thunderstorms and fair weather.

Average temperature (°C)	Stations	From 2012 to 2019						
		April	May	June	July	August	September	October
during fair weather	Aragats	0.15	5	9.3	12.7	12.6	9.5	4.87
	Nor Amberd	7.6	12.3	16.7	19.6	20.5	17.8	11.6
	Yerevan	11.9	17.3	21.9	26	26.3	23	13.6
during thunderstorm	Aragats	−1	0.6	4.9	7.2	8.4	5.5	−4.1
	Nor Amberd	5.9	9.6	13	12.8	14.3	11.1	10.7
	Yerevan	12.4	16.4	15.3	–	–	15.8	–

2.3. Meteorological parameters behavior during fair weather and thunderstorms

According to the past investigations, thunderstorm activity has correlation with the meteorological parameters (Manohar et al., 1999). For revealing any possible connection between meteorological parameters behavior during fair weather and thunderstorms we have investigated atmospheric pressure, wind speed, temperature and humidity during the above discussed cases from 2012 to 2019. As it was mentioned electric field discussion part, fair weather we have taken period of the day when the electric field is in the range from +0.01 to +0.99 kV/m and the registered wind speed is less than 6 m/s.

Fig. 4a is showing the distribution of the minimum temperature during thunderstorms. The ranges are between −5 °C and 10 °C at Aragats research station. This was also reported in Chilingarian et al., (2020): same temperature interval for thunderstorms, which accompanied with Thunderstorm ground Enhancement.

At Nor Amberd and Yerevan stations we observe a similar picture, with minimum temperature during thunderstorms ranging from 3 °C to 20 °C (25 °C at fair weather) and 10 °C–30 °C (reaching to 30 °C at fair weather) respectively (see Figs. 4a and 5a).

During thunderstorms outside humidity can reach up to 98% at Aragats station (see Fig. 4b), while at lower altitudes (at Nor Amberd and Aragats stations) it is almost 80%. The pressure at all three stations was distributed similarly for fair weather and thunderstorms (see Figs. 4c and 5c).

Our investigations also show that during thunderstorms wind speed was most frequently registered between 5 m/s and 10 m/s at Aragats and Yerevan station, while at Nor Amberd station it was registered most frequently between 8 m/s and 13 m/s (see Fig. 4d). This can be a result of geographic location impact and will be further investigated in the future. During fair weather we have registered wind speed mostly 3–5.5

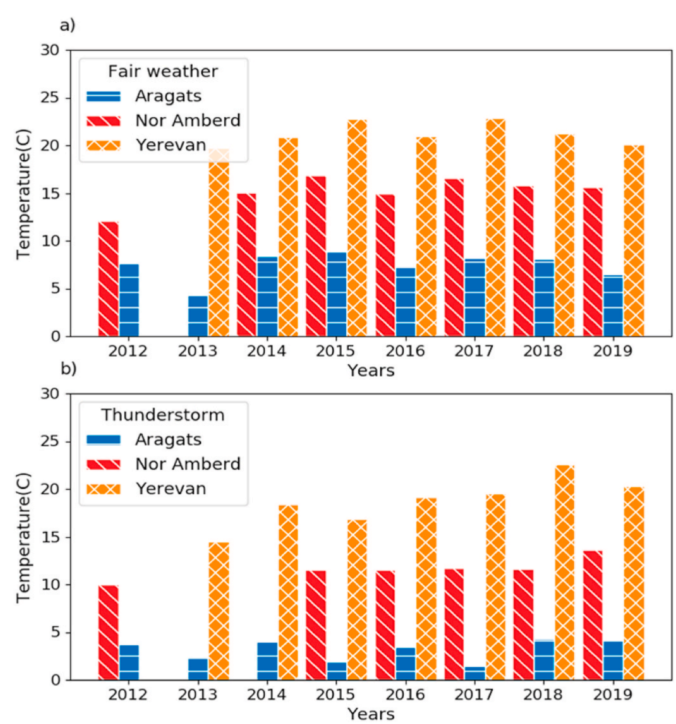

Fig. 6. Average annual distribution of temperature during fair weather (a) and thunderstorms (b).

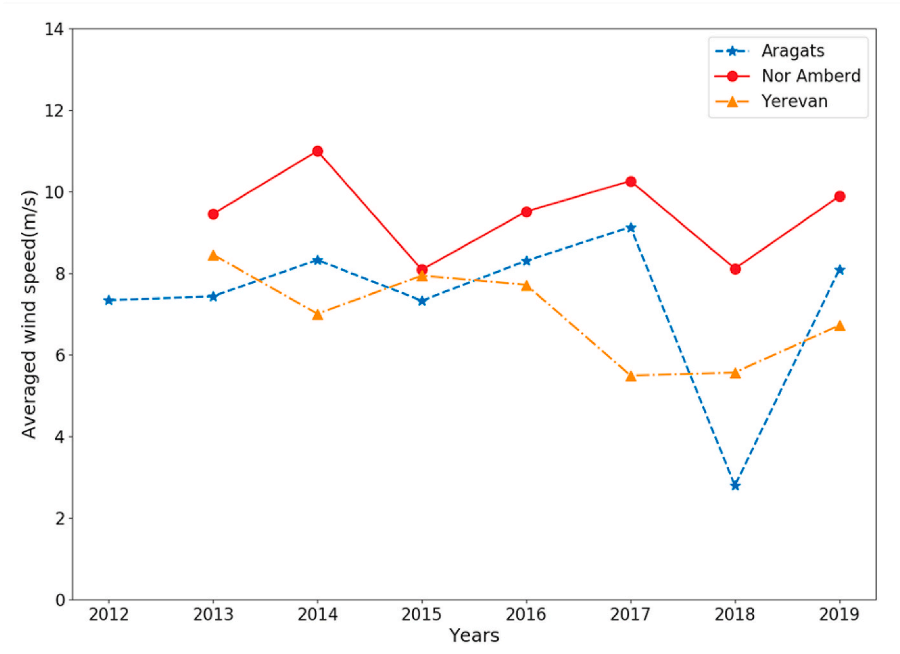

Fig. 7. Average maximum wind speed during thunderstorms for 2012–2019.

m/s in 3 stations (see Fig. 5d).

Average temperature during thunderstorms and fair weather are presented in Table 3. In the row 3 to 5 the average of mean temperature during 08:00–12:00 LT for each fair weather day is taken.

During each thunderstorm from 2012 to 2019 the average temperature for the same time interval is shown in the rows from 6 to 8 of Table 3. Mentioned period was chosen as a result of investigations of thunderstorms daily distribution (see Fig. 3c). As you can see from Fig. 3c there is less activity in the early morning hours and we have more fair weather cases for the mountain region.

At Aragats and Nor Amberd stations the highest average temperatures respectively 8.4 °C (12.6 °C) and 14.3 °C (20.5 °C) have been registered in August during thunderstorms (fair weather). In Yerevan the highest temperature was expected during July–August, but the thunderstorm are very rare during these months and from 08:00–12:00 LT we didn't register any of them for mentioned 2012–2019 period but we have registered fair weather with the highest average 26.11 °C temperature during July. The difference between temperature during fair weather and thunderstorm prompt us to sum up: at Aragats station clouds are almost sitting on the station during warm weather, therefore we don't have big temperature difference between fair weather and thunderstorm in this location comparing to Nor Amberd station.

Investigation of data from 2012 to 2019 are showing fluctuation of temperature during fair weather and thunderstorms (see Fig. 6). Even data is for 8 years but it is still possible to see temperature variation tends to be positive. During fair weather (see Fig. 6a) in this stage we cannot claim that temperature will increase in the upcoming years or not, but according to Fig. 6b we can see an increase of outside temperature in all stations. Overall, the lowest average temperature during thunderstorms was observed in 2013 at Yerevan (14 °C) and in 2017 at the Aragats station (2 °C). In Nor Amberd it is increasing from 2012 to 2019.

Vantage Pro 2 which is installed at Nor Amberd station was not working properly in 2013, therefore data for the mentioned year was erased from calculations.

From 2013 to 2019 at Yerevan station average of wind speed maximum is in the range from 5 m/s to 8.5 m/s, at Nor Amberd-from 8 m/s to 11 m/s and at Aragats-from 2 m/s to 9 m/s (see Fig. 7). As we can see, although, the Aragats is the highest station, but the wind speed is higher on the slopes of mountain where Nor Amberd station is located. At first the gap in 2018 at Aragats was interpreted as the luck of data, but further investigations in other stations showed that, indeed, in 2018 we have weak wind comparing to previous and next years. In addition, the distributions of wind speed during thunderstorms are not showing relation with thunderstorm activity (see Figs. 3a and 7). But we can see the decrease in Aragats and Nor Amberd stations during 2018, when thunderstorms also were less compared to previous years.

Wind direction distribution for Aragats, Nor Amberd and Yerevan

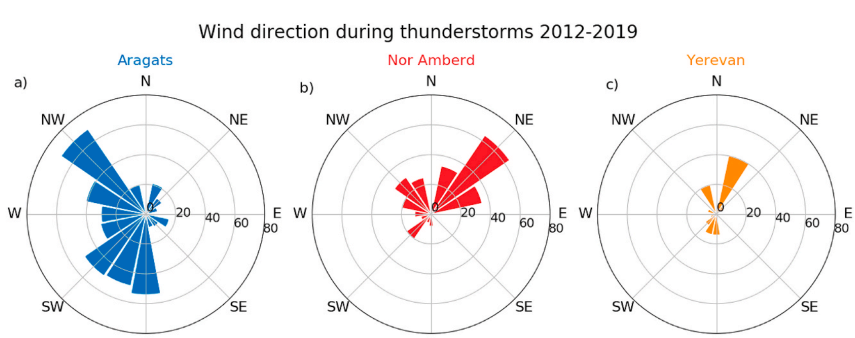

Fig. 8. Distribution of wind direction during thunderstorms from 2012 to 2019.

research stations is depicted in Fig. 8. In the wind roses is shown the most frequent direction of the wind during thunderstorms. At Aragats station, the most frequent direction was Northwestern, while at Nor Amberd and Yerevan stations wind blew predominantly from the Northeast. It should be noted that Aragats station is located on the northwestern side from Nor Amberd and Yerevan station. However, further studies will reveal full explanation for wind directions distributions.

3. Summary

First time, for different sites in Armenia the thunderstorm activity and fair weather studies have been done in this work based on near surface electric field measurements and meteorological parameters. Daily, monthly and annual thunderstorm distributions have been presented at different geographic locations from 2012 to 2019. The diurnal variations of near surface electric fields during fair weather also have been discussed.

The electric field behavior during a thunderstorm is strongly connected with fair weather. Fair weather and thunderstorms along with the lightning are the part of global electric circuit. Measurements, which are implemented in our stations, have been used for a better understanding fluctuation of the atmospheric electric field in local scales.

Fair weather study in Yerevan and Dilijan has been done for the first time. The investigations reveal that the fair-weather electric field at Dilijan research station is negative. This will be further investigated in our future works. We also see consistency of Yerevan station electric field variation with the Carnegie curve and addition to the measurements in early morning hours at Dilijan station, which we are connected to the Austausch effect and possible local pollution as the stations are inside the cities.

Consequently, our investigations are consistent with previous studies and showed that thunderstorm activity is high at higher altitudes. In all observed stations the daily thunderstorm activities coincide and reach the highest points from 15:00 to 20:00 LT. The region is very active with lightning strikes and at all three stations the most active period is in May–June and it is decreasing in September. Our studies show that on average the longest lasting thunderstorms observed at Aragats and Nor Amberd research stations were registered in June, while at Yerevan station they were registered in September. We also found that in all three stations shortest lasting thunderstorms were observed in October. The annual distribution of the storms is prompting about possible decrease in upcoming years, which should be studied further.

In this work we have discussed also meteorological variations. The difference between temperature during fair weather and thunderstorm reveal that at Aragats station clouds are almost sitting on the station during warm weather, therefore we don't have a big temperature difference between fair weather and thunderstorm for this location comparing to other stations. Wind speed studies showed that although the Aragats is the highest station, but the wind speed is higher on the slopes of mountain where Nor Amberd station is located.

Paper leaves open questions for more deeply investigation of the connections between meteorological parameters and electric field measurements. So, we intend to answer them during future research and find more connections with the global electric circuit.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors thank the staff of the Aragats Space Environmental Center for the uninterruptible operation of Aragats research station facilities. The authors also are thankful to the participants of seminar in Cosmic Ray Division for useful discussions and valuable comments. The analyses presented in the paper were supported by award from the Armenian National Science and Education Fund (ANSEF).

References

Chilingarian, A., et al., 2020. Structure of thunderstorm ground enhancement. Phys. Rev. D 101, 122004.
Chilingaryan, S., Beglarian, A., Kopmann, A., Voekling, S., 2010. Advanced data extraction infrastructure: web based system for management of time series data. J Phys Conf Ser 219, 042034.
Kumar, R., 2017. Lightning, rainfall, AOD, and convection variabilities in the monsoon zone of India. Int. J. Rem. Sens. 39, 3.
Manohar, G.K., Kandalgaonkar, S.S., Tinmaker, M.I.R., 1999. Thunderstorm activity over India and Indian southwest monsoon. J. Geophys. Res. 104.
Marshall, T.C., Rust, W.D., Stolzenburg, M., Roeder, W.P., Krehbiel, P.R., 1999. A study of enhanced fair-weather electric fields occurring soon after sunrise. J. Geophys. Res. 104 (D20), 24455–24469. https://doi.org/10.1029/1999JD900418.
Mkrtchyan, H., 2018. Study of atmospheric discharges by near surface electric field measurements. Open Atmos. Sci. J. 14 (1874–2823), 21–32. https://doi.org/10.2174/1874282301812010021. In press.
Nicoll, K., et al., 2019. A global atmospheric electricity monitoring network for climate and geophysical research. J. Atmos. Sol. Terr. Phys. 184, 18–29. March 2019.
Ranalkar, M.R., Chaudhari, H., 2019. Seasonal variation of lightning activity over the Indian subcontinent. Meteorol. Atmos. Phys. https://doi.org/10.1007/s00703-009-0026-7.
Torreson, O.W., Gish, O.H., Parkinson, W.C., Wait, G.R., 1946. Results of cruise VII of the Carnegie during 1928/1929 under command of captain J. P. Ault—oceanography III: ocean atmospheric-electric results. In: Publ.568. Carnegie Institution, Washington.
Turman, B.N., Edgar, B.C., 1982. Global lightning distributions at dawn and dusk. J. Geophys. Res. 87 (C2).
Whipple, F.J.W., 1929. On the association of the diurnal variation of the electrical potential gradient in fine weather with the distribution of thunderstorms over the globe. Quart. J. Roy. Met. Soc. 55.
Williams, E.R., 2009. The global electric circuit: a review. Atmos. Res. 91.
Yaniv, R., Yair, Y., Price, C., Mkrtchyan, H., Lynn, B., Reymers, A., 2017. Ground-based measurements of the vertical E-field in mountainous regions and the "Austausch" effect. Atmos. Res. 189.