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Ground-based measurements of the vertical E-field in mountainous regions and the "Austausch" effect

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Abstract:

Past measurements of the atmospheric vertical electric field (Ez or potential gradient) at numerous land stations showed a strong response of the daily electric field to a morning local effect known as "Austausch" – the transport of electrical charges due to increased turbulence. In mountainous regions, nocturnal charge accumulation, followed by an attachment process to aerosols near the surface in valleys, known as the electrode effect, is lifted as a charged aerosol layer by anabatic (upslope) winds during the morning hours due to solar heating.

Ground-based measurements during fair weather days were conducted at three mountain stations in Israel and Armenia. We present results of the mean diurnal variation of Ez and make comparisons with the well-known Carnegie curve and with past measurements of Ez on mountains. We report a good agreement between the mean diurnal curves of Ez at various mountain stations and the time of local sunrise when the Ez is found to increase. We attribute this morning maximum to the Austausch (or exchange) layer effect. We support our findings with conduction and turbulent current measurements showing high values of ions and charged aerosols being transported by winds from morning to noon local time, and by model simulations showing the convergence of winds in the early morning hours toward the mountain peak.

1. Introduction

The atmospheric fair weather electric field (Ez) is one of several observable parameters (along with the conduction current and atmospheric conductivity) that are used for studying the diurnal and seasonal behavior of the global electrical circuit (GEC) during fair and severe weather days (Rycroft et al., 2000).

The Ez observations shows a pronounced diurnal variation with a maximum around 19 UT and a minimum around 3 UT that correlates positively with global thunderstorm activity (Whipple 1929). The fair weather electric field values ranging from +100 to +300 V/m (pointing downward), with a clear seasonal variability, reflect changes in global lightning due to the movement of the ITCZ north and south of the equator (Harrison, 2013). While the original Ez observations (Carnegie Curve) were obtained from measurements over the oceans, land-based observations of Ez show that local meteorology and aerosol variations can lead to significant variability in the diurnal Ez behavior, especially in the morning hours. Aerosols are known to decrease the conductivity and therefore, for maintaining a constant vertical current density in the global circuit (in accordance with Ohm's law), they cause an increase in Ez (Sapsford, 1937; Schonland 1953a; Chalmers, 1967; Harrison, 2006; Aplin, 2012; Rycroft et al., 2012; Anisimov et al., 2011, 2014; Williams and Mareev, 2014; Yaniv et al., 2016).

The electrode effect refers to an electrical phenomena occurring in the lower atmosphere near the ground (ground level and up to 65 cm). It is the accumulation of positive space charge (up to 4000 charges/cm^3 with a mean of ~1500 charges/cm^3) above the negative Earth during night time at periods of low wind (less than 1m/sec) and almost no turbulence (Crozier 1963). This effect is a result of the ground being the negative electrode of the parallel-plate capacitor between the Earth and ionosphere, attracting positive ions within the skin-layer and small parcels of screening negative layer above it (65-80 cm) (Crozier 1963). Measurements of charge density, Ez, wind and temperature in the boundary layer reported high concentrations of charges when the wind was low. High wind speeds (>2m/sec) result in large Ez variations due to turbulence associated with the movement of pockets of space charge by the wind (Bent and Hutchinson, 1966). Kamra (1982) also reports observation of the electrode effect up to 2 meter above ground and found variabilities in the E field when the charged layer is mixed during sunrise.

Measurements and modeling of electrical charge transport by turbulent processes within the boundary layer were performed above land (Law 1963 and Willet, 1979) and above oceans (Fairall et al., 1981). Law (1963) observed the "sunrise effect" which is a sharp increase of the E field in the morning due to the increase of aerosol concentration. Willet (1979) investigated the hypothesis of thermal convection chimneys which carried charge upward from the charge layer to higher altitudes. He found that convection in unstable boundary layers over land, using the electrode effect as the source, is the main influence on local atmospheric electricity, and can be the possible explanation of diurnal variations observed at land stations. Fairall et al. (1981) suggested that over the oceans, the positive electrode effect (~100 charges/cm^3) that is produced by breaking waves and the downward flow of positive ions by the conduction current is more observable since no negative charge is present (no radioactive ionization in the absence of solid ground). This charged layer was found to be transported upward by eddy diffusion in the same manner as water vapor and heat. Willet (1983) concluded that convection of charge in the electrode layer can produce upward turbulence currents with magnitudes of 60-90% of the total fair weather current density.

Measurements in West Africa showed the "Austausch" effect in the lower boundary (exchange) layer when dry winds from the Sahara Desert fill the area with fine dust, and meet the moist trade winds of the south Atlantic. At morning hours, when the night inversion collapses in the hours after sunrise, the haze clears and dust at higher levels is dispersed, causing a strong response of the Ez (Ette, 1971). Weiss et al. (1976) suggested that this is caused by convective "bubbles" that carry low-conductivity air to higher altitudes. Hoppel et al., (1986) suggested that in a turbulent atmosphere, the convective flux of charge extends to higher altitudes. He showed that columnar resistance is higher during the morning hours, reaching peak values around noon due to upward convection of aerosols and charge. Higher columnar resistance is manifested at the surface as higher values of the electric field (Chalmers, 1957).

The conduction current J_Z is regarded as the current that flows in the Earth's global circuit, due to the potential difference between the ionosphere and the surface. The vertical conduction current (J_Z) is one of the components that contribute to the total current J_S, in addition to the contributions from the displacement current J_D and the turbulence current J_T. The displacement current J_D is defined as a current that is caused by temporal changes in the electric field (e.g from passing clouds and short gusts of wind). The turbulence current J_T is caused by the physical transport of space charge. The total current Js is therefore the sum of the J_Z, J_D and J_T (Bennett and Harrison 2008). Ground based measurements recently found an increase of the vertical conduction current (Jz) during periods of strong wind, indicating the variability in conductivity due to changes in the wind velocity (Elhalel et al., 2014).

This study presents new data from 3 mountainous stations – one in Israel and two in Armenia - showing the response of the vertical component of the electric field (Ez) and the conduction and turbulence currents densities (J_Z and J_T) from early morning to midday, due to the effect of upslope winds and the advection of a charged aerosol layer from the valleys below.

2. Instrumentation and Observation sites

The Israeli station on Mt. Hermon is equipped with a CS110 electric field mill by Campbell Scientific Company (http://www.campbellsci.com/cs110-

sensor). The CS110 measures the vertical component of the electric field (Ez) at a sampling frequency of 1 Hz. It is placed on top of a 2 meter high mast that is attached to a 1 meter high heavy tripod (Yaniv et al., 2016). The Geometrical Displacement and Conduction Current Sensor (GDACCS) is composed of two electrode plates to measure the vertical conduction current Jz in the atmosphere at a sampling frequency of 10 Hz and was developed at the Meteorology Department in the University of Reading, UK (Bennett and Harrison, 2008). Both stations are permanently placed on Mount Hermon (33^{o}18'N 35^{o}47.2'E, altitude 2100m) on a flat hill surrounded by deep valleys. Wind speed values in Mt. Hermon and in Damascus and Kibbutz Dafna (that are located to the east and west of the mountain range, respectively) were obtained using meteorological stations at each site. However, due to the lack of wind direction data, the average wind direction was obtained using the Weather Research and Forecasting (WRF) model to study the winds in the areas surrounding the Hermon mountain range, which are the Hula valley to the west and the Golan Height and the Damascus plateau to the east. Global Forecast Model (GFS) input files were used to initialize the model (Lynn et al 2012). We simulated 15 fair weather days in July 2015 which are representative of the average conditions in summer. There was no rain during the period, and only very few clouds.

The Armenian stations are equipped with an EFM-100 electric field meter by Boltek company (http://www.boltek.com/product/efm-100-electric-field-monitor). The EFM-100 is placed on a 1 meter tripod on top of the cosmic station's roof with overall height of 8 meter above ground, and it measures the static electric field at a sampling rate of 20 Hz. The first station is located at Nor Amberd (40^{o}22'N, 44^{o}15.5'E, altitude 2000m), and the second station is at Mount Aragats (40^{o}28'N, 44^{o}11'E, altitude 3200m) – both stations are part of the cosmic ray monitoring network in Armenia (Chilingarian and Mkrtchyan., 2012).

3. Results

We first describe the diurnal variation of the vertical electrical field component at the three sites. Table 1 summarizes the results from Mt. Hermon, Nor Amberd and Mount Aragats respectively, with Ez [V/m] values shown around the local mean [%] of each station. Figure 1 shows the fair weather mean diurnal variability of the Ez as a function of the universal time (UT) from the three stations, plus the well-known marine Carnegie Curve, and an additional mountain curve from Davos, Switzerland (based on Israël., 1970). The Mt. Hermon curve is deduced from 50 fair weather days (April 2015 – November 2015) that were defined as days with no recorded geomagnetic activity from space weather events and days with no thunderstorm and significant dust events in the region (this is verified by using the relevant meteorological information). The Nor Amberd and Mount Aragats curves are deducted from 408 and 403 fair weather days (June 2011 – April 2016), respectively, that were defined as days with no clouds (using a 360^0 sky camera), and wind speed lower than 6 m/s (using a meteorological station).

The minimum values of the curves are around 02:00-03:00 UT and are well-correlated (note that both Israel and Armenia LT = UT+2). The minimum values correspond to the low lightning activity above the Pacific Ocean (Harrison, 2013). In all mountain plots there is an early morning to noon (04:00-14:00 UT) peak that is absent from the Carnegie curve. We assume that the local effect is caused by the dynamics of the exchange ("Austausch") layer. The secondary maximum value of all curves is found around 19:00-20:00 UT and correspond to the high lightning activity above the Americas reported in past and recent research papers (Whipple, 1929; Mezuman et al., 2014 and Yaniv et al., 2016).

Crozier (1963) and Bent and Hutchinson (1966) showed the generation of an electrode layer at night with winds around 1m/s and no turbulence, resulting in charge accumulation near the ground. Fair weather analysis using wind speed data from meteorological stations (122 and 25 fair weather days from spring and summer 2015) that are located at the foot of Mt. Hermon (Kibbutz Dafna 33°13′N 35°38′E, altitude 141m – 15.5 km aerial distance south-west of Mt. Hermon; and Damascus 33°24′N 36°30′E, altitude 620m – ~50 km aerial distance north-east of Mt. Hermon) are presented in Figure 2a. It shows that during night the wind speed is low (0.5-1.5 m/s) and meets the condition for generation of the electrode effect. The increase of wind in Damascus and the Syrian Golan heights begins around 5:00 UT and gradually intensifies to values higher than 2m/s and in Kibbutz Dafna this occurs around 6:00 UT– enough to eliminate the electrode layer and the nocturnal inversion layer (Crozier, 1963). The increase of wind at Mt. Hermon starts around 06:00-06:30, around 0.5-1 hour after the increase observed in the surrounding lower areas. The difference represents the mean time is takes the anabatic wind to climb up the mountain slopes (~1900 meter). This is the time in which the boundary layer inversion collapses due to solar heating in the morning hours. Figure 2b shows the wind acceleration mean curve in Mt. Hermon derived from the wind acceleration profile as a function of time, showing that the maximum wind speed positively correlates with the peak in the fair weather E-field curve. Figure 2c shows the wind profiles of more than 400 fair weather days from 2011 to 2016 that were measured at Nor Amberd and Mt. Aragats, with increases in wind speed easily noticeable around 04:00 - 05:00 UT.

Evidence of the uplifting of the charged aerosol layer to the mountain top in the morning hours is demonstrated by using monthly curves, which reflect the changing sunrise times at each location and by inference, the onset of eddy diffusion and turbulence. As the sunrise hour becomes earlier during spring and summer, the heating of the ground and the onset of convection of the charged layer occurs at earlier times. There is a delay in the response of the Ez at the mountain sites, reflecting the upslope movement of air (e.g. anabatic winds) that accumulated during night at lower altitudes (Figure 2). Figure 3a shows the summer and winter Ez measurements from Mt. Hermon, with the increase of Ez correlated with the sunrise hour for each month (earlier for summer and later in the winter). Figure 3b shows the same effect measured for Nor Amberd and Mount Aragats. The increase of Ez starts earlier in summer and later in winter months.

To further investigate the link between wind direction and the Austausch effect, we performed a few simulations of the boundary layer winds using the WRF model. Figure 4a-h shows a model run simulating the conditions during 14-29 July, 2015, from early morning to noon. The model maps show the topography of the Mt. Hermon vicinity (shading) clearly showing the Hermon mountain area as a convergence zone of winds (arrows) from all directions from 5:00 to 9:00. The westerly sea breeze from the Mediterranean Sea begins to dominate from 9:00 and so the effect of the early morning hours is being wiped out. Although we do not have in-situ aerosol data, it seems reasonable to assume that the air transported from the Damascus region contains significant air pollution and possibly smoke from the on-going hostilities in Syria.

In addition, Figure 5 shows the conduction current density (J_Z) and the turbulent current density (J_T) profiles during 50 fair weather days on Mt. Hermon. The Jz fair weather days are for the same days of the Ez analysis. The peaks in the J_Z correlate positively (R=0.67) with the peak in the Hermon Ez (Figure 1) indicating that an increase in Jz during times of increase in the Ez, as can be expected from Ohm's law. The morning peak in the fair weather profile of the turbulent current density J_T supports the assumption of charge movement across the sensor in the morning hours, when winds increase and charged particles are lifted up the slopes of the mountain. The increase of Jz is 80% during the "Austausch" period in the morning hours compared with other hours of the day and similar to the 60%-90% values reported by Willet (1983).

4. Summary

We report results of the fair weather electric field measurements conducted in 3 mountain sites in Israel and Armenia. In all three locations, we show that the vertical component of the fair-weather electric field (Ez) correlates positively with the well-known Carnegie curve at night (Pacific low) and late evening (Americas lightning activity), but exhibit a strong local morning to noon peak, which is missing from the Carnegie curve (Harrison, 2013).

We suggest that during the night the low hills at the foot of mountains accumulate charge due to the electrode effect. After sunrise the nocturnal boundary layer inversion collapses as solar insolation increases and the surface winds intensify. The Ez increase that is observed at mountain stations reflects an increase due to the rise of the charged aerosol layer to the mountain top as the sun heats the ground in a phenomena known as exchange layer or “Austausch”. However, we conclude that the main effect is caused by an increase in aerosol concentrations, resulting in a decrease in conductivity, followed by a rise in Ez. The summer/ winter analysis shows that the maximum morning increase in the vertical component of the fair-weather electric field follows the time of local sunrise. In addition, using the WRF model to simulate the wind direction in the morning hours, we show that the mountain is effectively a convergence zone for the surrounding area. Turbulent current density measurements also show a significant peak in the morning hours which is likely due to charged aerosols carried by the anabatic winds and passing the sensors.

Acknowledgments

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Figure Captions:

Figure 1. Diurnal (percentage from the mean) Ez curves from Davos Swiss [Israël 1970], Hermon Israel, Nor Amberd Armenia and Aragats Armenia.

Figure 2a. Wind speed profile from Mt. Hermon and from Damascus Syria, located on the low hills north east from Mt. Hermon.

Figure 2b. Acceleration profile (dv/dt) from Mt. Hermon versus the Ez fair-weather curve.

Figure 2c. Fair weather wind profile from Aragats and Nor Amberd, Armenia.

Figure 3a. Summer / Winter comparison of Ez variations as measured on Mt. Hermon, Israel.

Figure 3b. Summer / Winter comparison of Ez variations as measured on Nor Amberd, Armenia.

Figure 4a-h. WRF simulations showing the change in wind direction in the vicinity of Mt. Hermon from 5:00 to 12:00 (mean values of 15 fair weather days).

Figure 5. Conduction current (Jz) and Turbulent Current (Jt) densities during fairweather days on Mt. Hermon, Israel.

Table Caption:

Table 1. A 24 pt. resolution of the Mountain curves (Hermon, Nor Amberd, Aragats) with values around the mean. Annual mean [V/m]: Hermon = 290, Nor Amberd = 233, Aragats = 188.

Figures:

Figure 1:

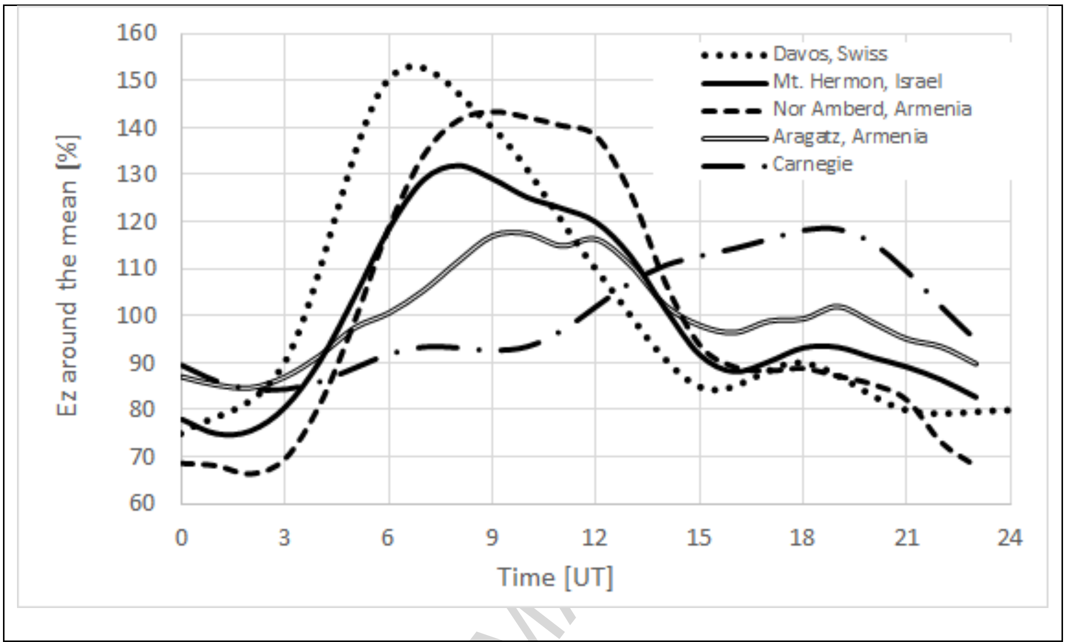


Figure 2a:

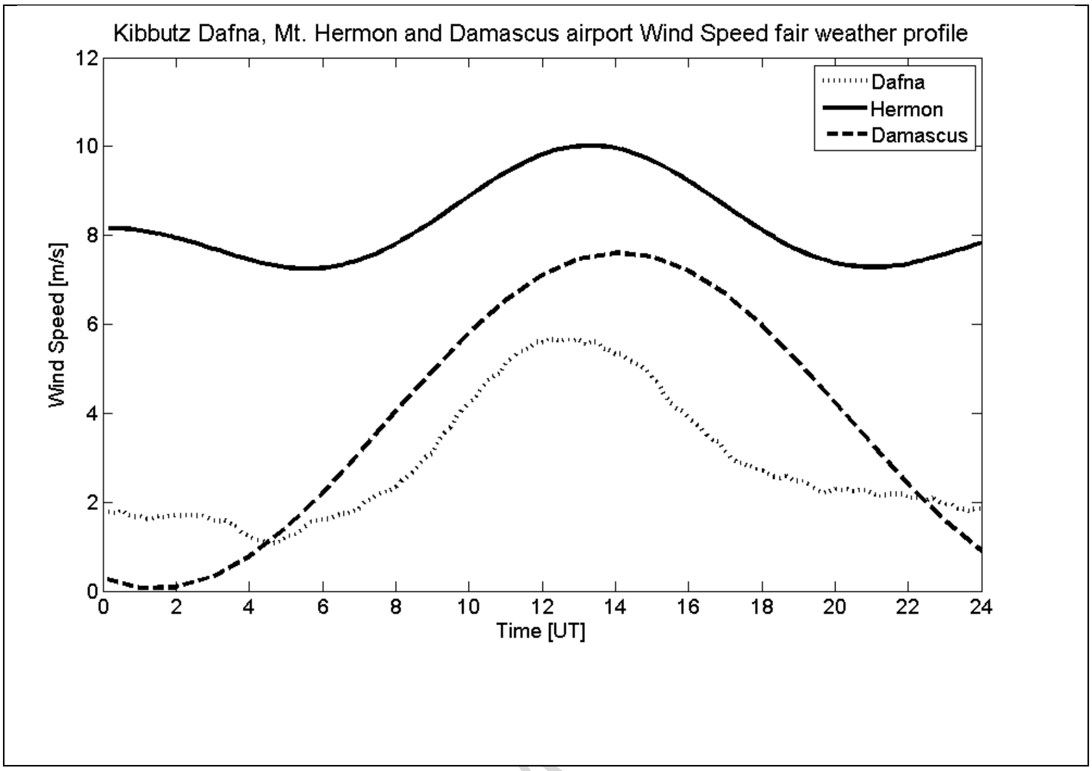

Kibbutz Dafna, Mt. Hermon and Damascus airport Wind Speed fair weather profile
Dafna
Hermon
Damascus
Wind Speed [m/s]
Time [UT]
0
2
4
6
8
10
12
14
16
18
20
22
24

Figure 2b

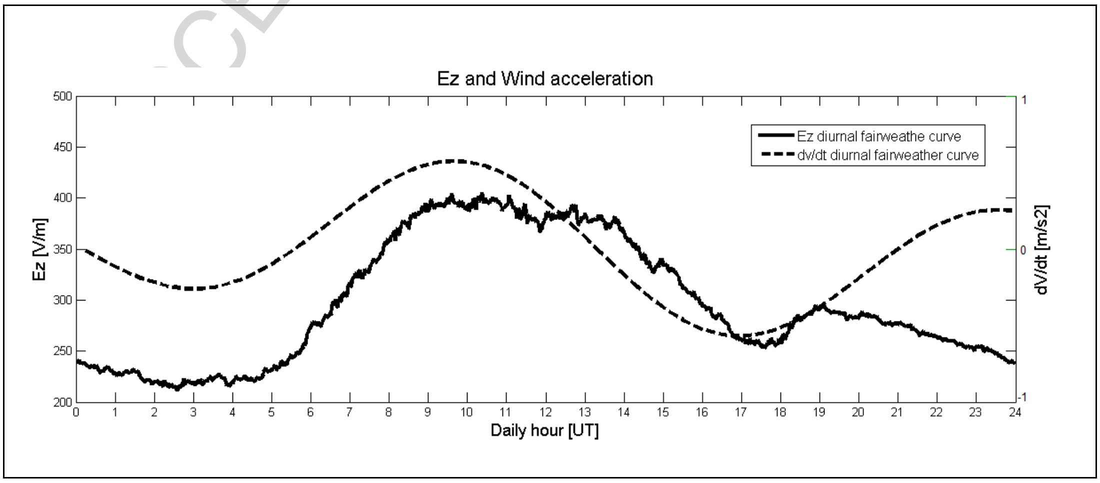

Ez and Wind acceleration
Ez diurnal fairweathe curve
dv/dt diurnal fairweather curve
Ez [V/m]
dV/dt [m/s2]
Daily hour [UT]

Figure 2c

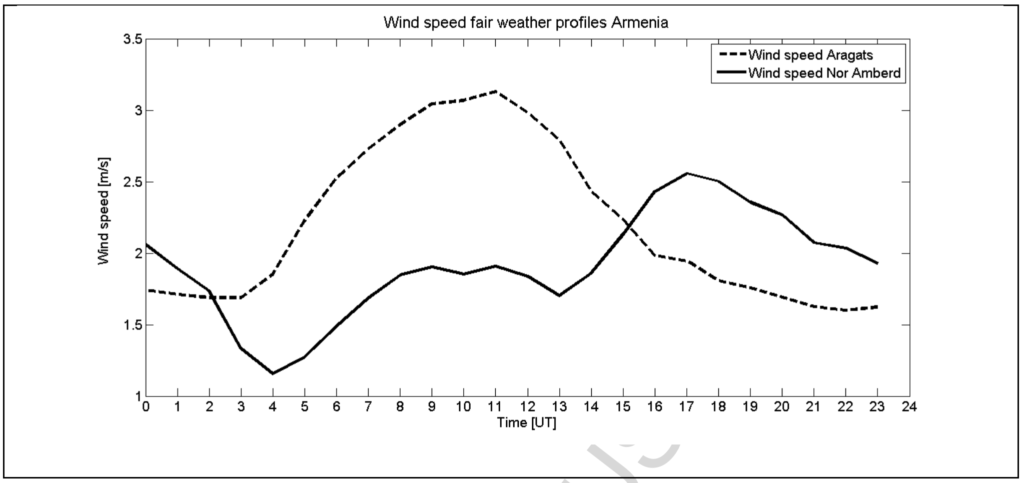


Figure 3a:

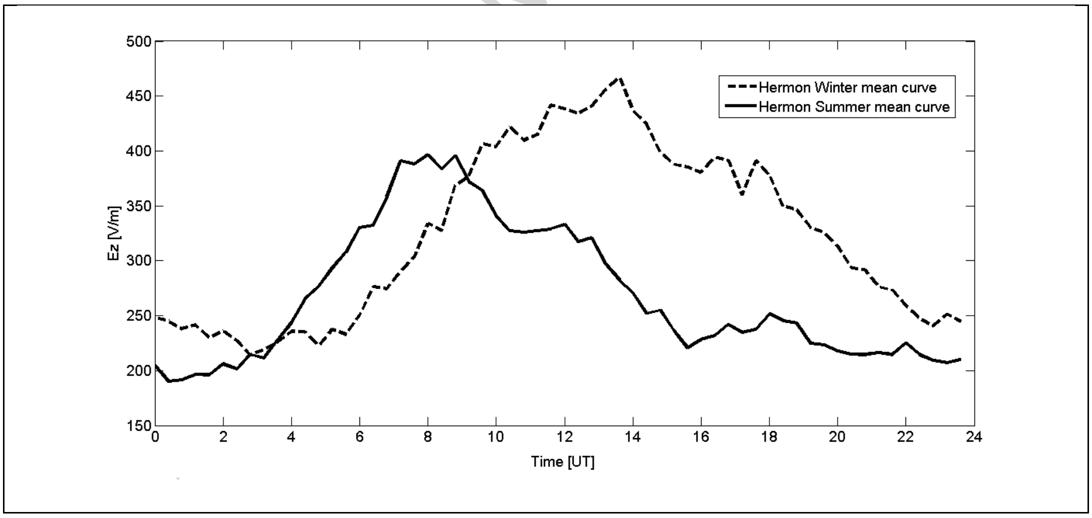


Figure 3b:

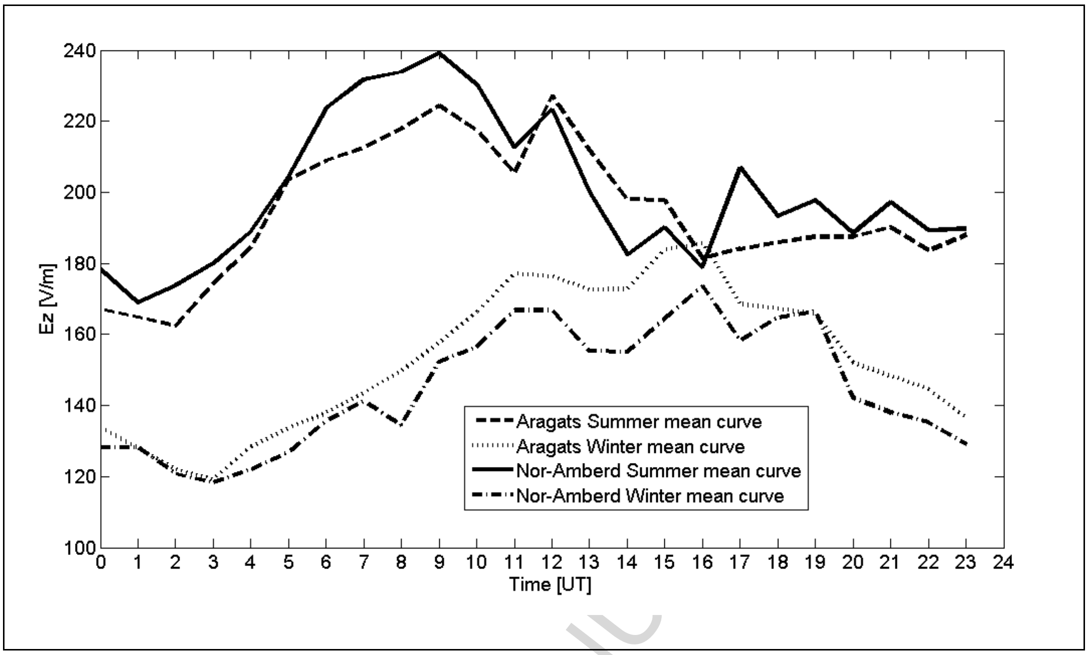
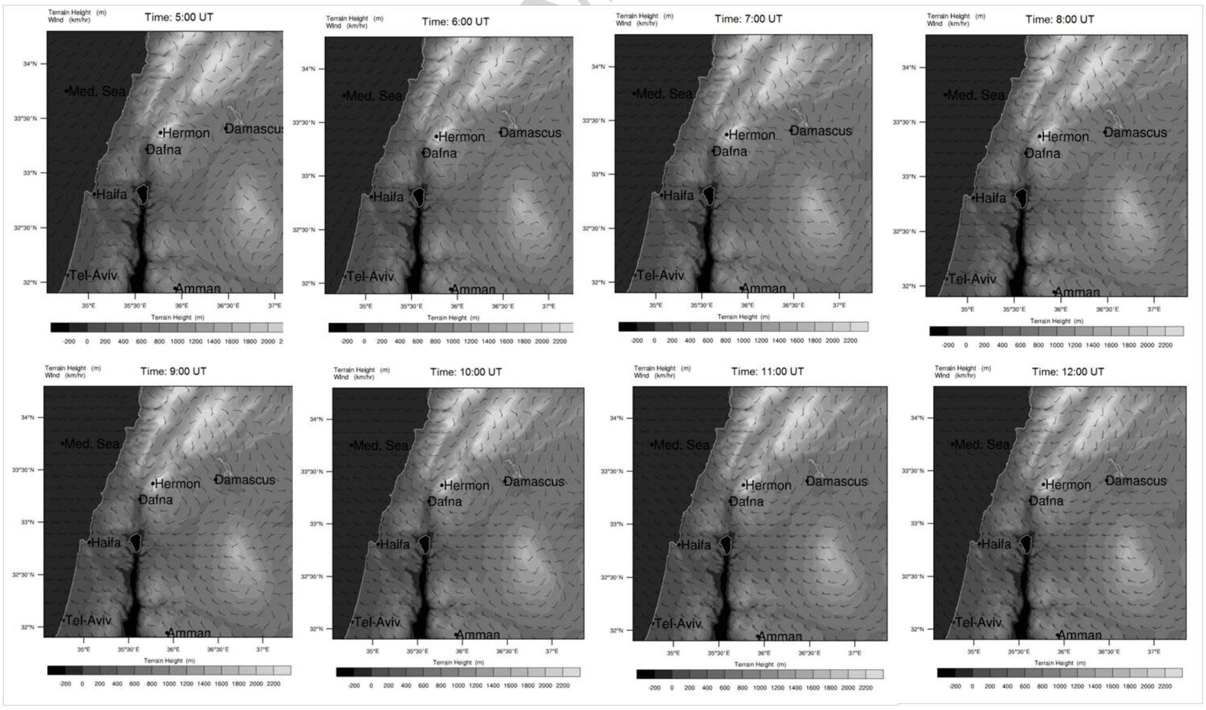

Ez [V/m]
Time [UT]
Aragats Summer mean curve
Aragats Winter mean curve
Nor-Amberd Summer mean curve
Nor-Amberd Winter mean curve

Figure 4:


Time: 5:00 UT
Time: 6:00 UT
Time: 7:00 UT
Time: 8:00 UT
Time: 9:00 UT
Time: 10:00 UT
Time: 11:00 UT
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Med. Sea
Hermon
Damascus
Dafna
Haifa
Tel-Aviv
Amman

Figure 5:

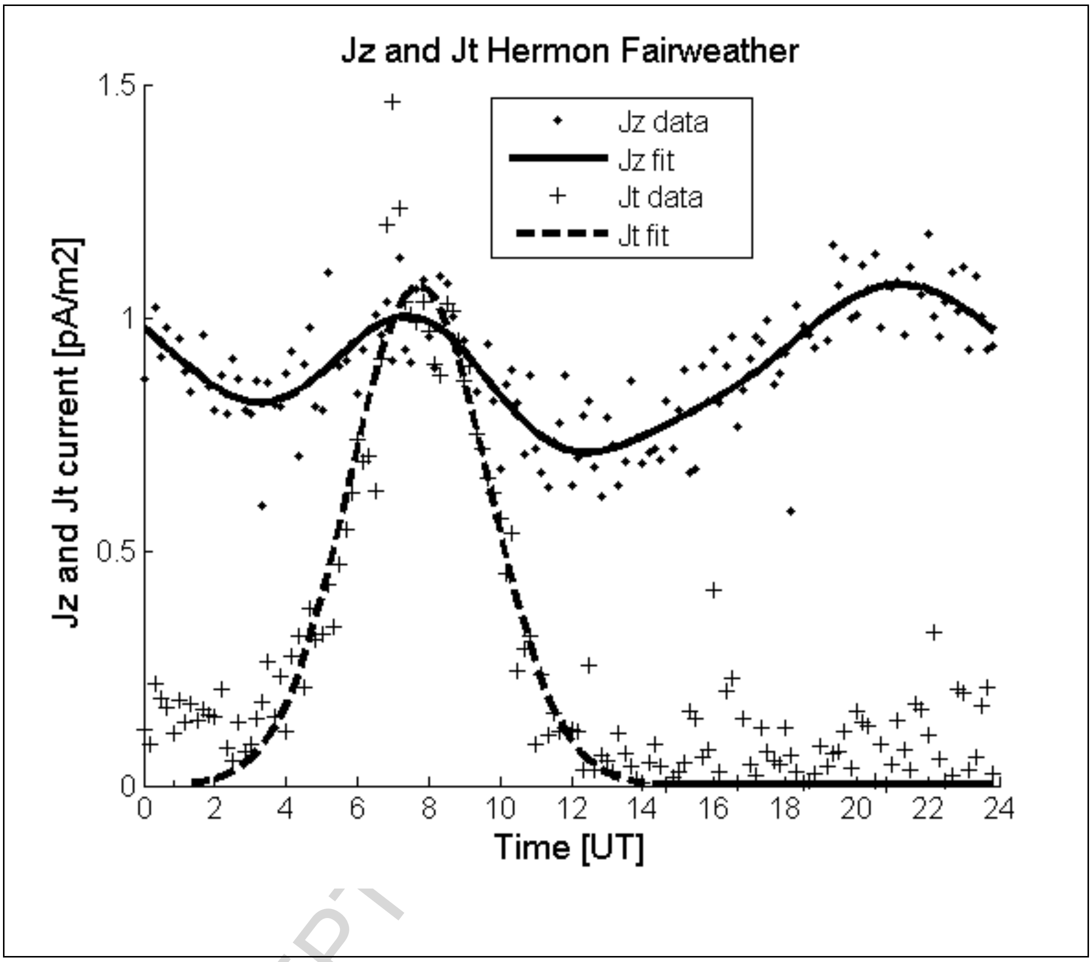
Jz and Jt Hermon Fairweather
Jz data
Jz fit
Jt data
Jt fit
Jz and Jt current [pA/m2]
1.5
1
0.5
0
0
2
4
6
8
10
12
14
16
18
20
22
24
Time [UT]

Table 1:

Diurnal fair weather Ez Mountain curves			
UT Time	**% from mean Hermon, Israel**	**% from mean Nor Amberd, Armenia**	**% from mean Aragats, Armenia**
0	78.0	68.5	87.0
1	74.9	68.0	85.3
2	75.5	66.3	84.7
3	80.6	69.5	87.0
4	90.3	81.1	91.5
5	103.9	98.7	97.4
6	118.5	118.9	100.6
7	128.9	134.2	105.3
8	131.9	141.7	111.5
9	129.1	143.5	117.0
10	125.2	142.4	117.4
11	122.9	140.6	114.9
12	119.9	138.3	116.3
13	112.6	126.1	110.7
14	101.5	107.1	102.2
15	91.7	93.7	97.9
16	88.1	89.1	96.4
17	90.2	88.2	98.8
18	93.2	88.7	99.3
19	93.3	87.1	101.9
20	91.1	85.4	98.6
21	89.1	82.0	95.0
22	86.4	73.0	93.4
23	82.7	67.9	89.8

Highlights

Ground-based measurements of the vertical E-field in mountainous regions and the "Austausch" effect by Yaniv et al. (2016)

- Combined measurements of the fair-weather electric field (Ez) in 3 mountain stations in Israel and Armenia
- A significant departure of the profile from the Carnegie curve is observed during morning hours in all stations.
- First numerical modeling of the surface wind-field shows a convergence of upslope (anabatic) winds after sunrise, carrying aerosols and pollution from lower heights
- Reduced electrical conductivity is manifested in intensification of Ez.