Atmospheric Research 196 (2017) 142–150

Contents lists available at ScienceDirect

Atmospheric Research

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

Ground level gamma-ray and electric field enhancements during disturbed weather: Combined signatures from convective clouds, lightning and rain

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ABSTRACT

We report coincidences of ground-level gamma-ray enhancements with precipitation events and strong electric fields typical of thunderstorms, measured at the Emilio Segre Cosmic Ray observatory located on the western slopes of Mt. Hermon in northern Israel. The observatory hosts 2 × 2″ Nal(TI) gamma ray scintillation detectors alongside a vertical atmospheric electric field (E_z) mill and conduction current (J_z) plates. During several active thunderstorms that occurred near the Mt. Hermon station in October and November 2015, we recorded prolonged periods of gamma ray enhancements, which lasted tens of minutes and coincided with peaks both in precipitation and the vertical electric field. Two types of events were detected: slow increase (up to ~300 min) of atmospheric gamma ray radiation due to radon progeny washout (or rainout) along with minutes of E_z enhancement, which were not associated with the occurrences of nearby CG lightning discharges. The second type showed 30 min bursts of gamma rays, coinciding with minutes of E_z enhancement that closely matched the occurrences of nearby CG lightning discharges, and are superimposed on the radiation from radon daughters washed out to near surface levels by precipitation. We conclude that a superposition of accelerated high energy electrons by thunderstorm electric fields and radon progeny washout (or rainout) explains the relatively fast near surface gamma-ray increase, where the minutes-scale vertical electric field enhancement are presumably caused due to nearby convective clouds. Our results show that the mean exponential half-life depletion times of the residual nuclei produced during events without lightning occurrences were between ~25–65 min, compared to ~55–100 min when lightning was present, indicating that different types of nuclei were involved.

1. Introduction

The levels of atmospheric gamma-ray radiation near the ground are determined by the natural local concentrations of radioactive agents such as ^{222}Rn, which percolates from uranium bearing minerals in the crust. The flux of Radon atoms is related to content of U-bearing minerals, the emanation of radon and the porosity of the soil – all of which can vary significantly between locations (Mercier et al., 2009). The natural background levels at any given place are also a function of the meteorological conditions. These levels are monitored for public-health reasons, but also in order to give early-warning in case of nuclear accidents and intentional terror attacks. Deviations from the background pattern of gamma-ray levels are related to precipitation processes and have been used to evaluate rain age (Greenfield et al., 2008). The increase in near surface gamma-ray levels is mainly due to the activity of radio nuclides such as ^{214}Pb and ^{214}Bi whose half-lives are 26.8 and 19.7 min, respectively, being scavenged by precipitation particles (rain drops or snow crystals), a well-known effect thoroughly discussed in the literature (Fujinami, 1996; Horng and Jiang, 2004; Livesay et al., 2014). The increase can be from a few to tens of percent compared to the background levels and depends on the rainfall rate (Takeyasu et al., 2006). For example, Burnett et al. (2010) reported gamma radiation levels exceeding by 125% compared with the mean background value in 9 distinct events of heavy precipitation near the Atomic Weapon Establishment site in Aldermaston, UK. They reported no correlation between the amount of rainfall and the dose rate increase, and the effect decreased back to normal values in 1–2 h. Recently, Hirouchi et al. (2014) reported a method for estimating the surface concentrations of the decay products in relation with gamma dose rate changes.

There are also seasonal patterns in the gamma-ray levels, related to

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http://dx.doi.org/10.1016/j.atmosres.2017.06.012
Received 3 February 2017; Received in revised form 20 April 2017; Accepted 13 June 2017

the geographical location and weather patterns (Inomata et al., 2007). Another source for observed increases in gamma-ray levels at the surface is attributed to thunderstorm and lightning activity (Greenfield et al., 2003; Ringuette et al., 2013). This mechanism involves the acceleration of protons by the strong electric fields within and below thunderstorms, which interact with the major components of air (nitrogen, oxygen, argon and carbon) and are decelerated to produce various types of radionuclides and brehmsstrahlung radiation (Greenfield et al., 2003). These are then transported downwards to the surface and deplete with exponential half-life depletion times of the order of ~55 min (see the Appendix in Greenfield et al., 2003 for details). Tsuchiya et al. (2011) also reported significant gamma-ray signals with minutes-scale duration and energy spectra extended to 10 MeV, and attributed these enhancements as products of relativistic electrons via brehmsstrahlung. An alternative explanation for short-lived (~few minutes) Thunderstorms Ground Enhancements (TGEs) of gamma-ray intensity observed at the surface was offered by Chilingarian and Mkrtchyan (2012) and Chilingarian (2014) who identified the Lower Positive Charge Center (LPCR) in thunderclouds as the acceleration agent. They attribute the rapid changes in the counts of gamma-rays at the surface to acceleration and multiplication of the stable background fluxes of secondary cosmic rays by the positive electric fields (i.e. E [kV m^{-1}] is directed away from the earth), specifically of downward moving electrons.

In this paper we present results from one year of measurements in northern Israel focused on two months of observations that include several precipitation and lightning events, when clear deviations from background values of the electric field and gamma-ray counts were observed. Section 2 presents the instruments and observation site, Section 3 describes the results where we distinguish between rain events with lightning and with rain only, and in Section 4 we conclude and discuss the coincidences, offering possible mechanisms.

2. Instruments

The Emilio Segre Cosmic-Ray observatory is located on Mount Hermon, near the triple border between Israel, Syria and Lebanon, (33°18′N 35°47.2′E) at an altitude ~2020 m MSL (Fig. 1). The mountain is steep and experiences strong winds and harsh weather conditions, especially in winter. The observatory is located on a small hill on the western flank of the mountain, and functions as part of the global neutron monitor network and records cosmic ray fluxes by using standard 6NM-64 detectors. It also measures basic meteorological parameters such as pressure, relative humidity, temperature and wind velocity. For monitoring the fair-weather electric field we used a CS110 electric field meter by Campbell Scientific Company, which measures the vertical component of the electric field (E_z) at a sampling frequency of 1 Hz. It is placed on top of a 2 m high mast that is attached to a 1-m high heavy tripod. For measuring the vertical conduction current density we used the Geometrical Displacement and Conduction Current Sensor (GDACCS), composed of two equal-area metal plates with a sampling frequency of 10 Hz (Bennett and Harrison, 2008; Elhalel et al., 2014). The meteorological parameters are obtained from an automatic weather station with 1 min resolution, but rain is collected at a separate station at a lower altitude (near the base-camp funicular station), a vertical separation of 500 m from the site. Rain gauge data are available at 30-min resolution, and although not measured at the Hermon site itself, the data represent the fact that it rained on the mountain (in reality, one can expect larger values of precipitation as we ascend higher up on the mountain). The detection of temporal variation of gamma radiation was achieved by using gamma detectors with 2 × 2″ NaI(Tl) scintillation detectors (PM-11; Rotem Industries Inc., Israel) tuned to the energy range of 50–3000 keV (Zafrir et al., 2011), sampling at 15-min resolution. The PM-11 is placed vertically on the local ground and a Pb shield is located above it, within the local observatory facility. This configuration leads to preferred detection of gamma rays from near surface air lateral to the detector.

Lightning data were obtained from the World Wide Lightning Location Network (WWLLN) and from the Israel Electrical Corporation (IEC), operating the Israel Lightning Detection Network (ILDN). The WWLLN determines the locations of lightning strokes based on the time of group arrival of at least 5 sensors, and normally only ~15–30% of strokes detected by one sensor are detected by 5 or more sensors. The strokes that are detected are usually the stronger ones, and recent studies indicates the WWLLN average global detection efficiency for strokes with peak currents > 30 kA is approximately 30% (Zheng et al., 2016). The ILDN system consists of 11 LPATS (based on time of arrival system) and IMPACT (based on both time of arrival along with magnetic direction and signal amplitude finding system) sensors (Cummins and Krider, 1998) distributed over the entire country from the Golan Heights to the Gulf of Eilat. Within the land area of Israel the stroke detection efficiency is > 80%, and it decreases with distance from the network center (Tel-Aviv area). The system registers cloud-to-ground strokes with a time accuracy better than 1 ms, where flashes with a current between 0 and +10 kA are automatically filtered out, being treated as intra-cloud flashes (Shalev et al., 2011).

3. Observations

The data acquisition of the surface electric field (E_z) at Mt. Hermon site is maintained as long as weather condition allows, because from December through March the mountain is completely covered in snow (Fig. 1c), sometimes to a depth of several meters. After spring melt, measurements resume continuously from April through late November. The electric field (E_z) at any given place is affected by the local atmospheric conductivity, space charge density close to ground, global lightning activity and ionospheric conditions (Elhalel et al., 2014). Therefore, the diurnal variation curve of E_z has a predictable shape depending on the location of measurement. The average E_z value at Mt. Hermon is a downward-pointing negative field ~290 Vm^{-1} and fluctuates between 220 and 600 Vm^{-1} (Fig. 2a red rectangle close-up). It exhibits a seasonal dependence reflecting changes in the local sunrise hour, as well as differences in global lightning activity. The background diurnal variation of the fair weather electric field at Mt. Hermon was investigated by Yaniv et al. (2017). It exhibits the pattern of global thunderstorm activity of the Carnegie Curve (Harrison, 2013) with an additional early morning peak typical of mountainous regions, likely due to the anabatic (upslope) winds transporting aerosols that are reducing the conductivity (thus increasing the E_z) from lower areas in the Damascus plateau in the east and the Hula valley in the west. The gamma-ray background levels at Mt. Hermon also exhibit variations consisting of diurnal and multi-day signals, likely caused by changes in Radon (^{222}Rn) concentrations in the local lowermost atmosphere (Fig. 2b). The diurnal variations show a 24-h periodicity, with an average count rate of 220–230 counts/15 min (Fig. 2c).

We now focus our attention on a series of observations in October–November 2015, when several precipitation episodes occurred in succession over the station. We distinguish between those events that exhibited lightning activity and those that were not accompanied by electrical activity, in the manner reviewed by Bennett and Harrison (2007) that separated between shower and non-shower clouds. The fact that Mt. Hermon is located ~2200 m above sea level implies a small vertical separation between cloud-base and the instruments, and so the travel-time of raindrops is just a few minutes at most. Table 1 summarizes 13 distinct events that are analyzed in this study.

3.1. Events of rain with no lightning

On October 7–9th 2015 there were eight distinct rain episodes registered by the rain gauge at the lower funicular station, all of which were accompanied by disturbances in the electric field and deviations from the gamma-ray background values. Based on tephigrams from the