



Nature of Relationships Between Atmospheric Electricity Parameters at Ground Surface and Air Ionization on the Basis of Nuclear Accidents in Power Plants and Weapons Tests

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In this work we present an analysis of selected atmospheric electricity parameters, measured at the Geophysical Observatory in Świder (near Warsaw, Poland), in a review of the major events that resulted in the release of a significant amount of artificial radioactive substances in the Earth's atmosphere: the radioactive accident in Fukushima, Japan, beginning 12 March 2011, followed by the 9.0 earthquake and tsunami; Chernobyl disaster (27 April 1986); and nuclear weapons testing (1958–1965). The physical mechanisms of the impact of radioactive sources on the electrical parameters of the atmosphere are analyzed. The formation of free charge (small ions, represented by electric air conductivity) and bound-induced charges (measured vertical electric field and current) by radioactive aerosol and cloud nuclei were taken into account. The values of electric field E_z , atmospheric air conductivity λ , and aerosol concentrations measured at a certain site depend on the time and space location of the released radioactive materials in relation to the measurement site and the meteorological situation. A frontal inflow of air masses containing radioactive substances may be noticeable at a large distance from the atmospheric electricity measuring site in fair weather conditions (Chernobyl disaster). Atmospheric precipitation plays a very important role in the transport of radioactive substances to the ground level (nuclear weapons testing). The relationship between the ionospheric potential V_i and the electric field near ground level E_z resulting from the Global Electric Circuit (GEC) concept for the presence of a strongly ionized air layer in the lower stratosphere and the ground level was disturbed in nuclear weapons testing time. The aim of this work is a qualitative characterization of discussed events. Future modeling works are needed to investigate the dependence of quantitative GEC parameters in situations of global or regional high air ionization. For this purpose, available measurements of recorded atmospheric electricity parameters will be used.

Keywords: atmospheric electricity, nuclear accidents, nuclear weapons testing, radioactive air pollution, ionizing

INTRODUCTION

Most of the issues discussed while analyzing the electricity of the atmosphere in connection with air radioactivity can be divided into the following groups: (1) experiments with nuclear weapons carried out in the high atmosphere in the years 1950–1965, (2) incidents of failure of nuclear power plants, Chernobyl, Fukushima, and regular releases from nuclear fuel reprocessing plants, (3) natural radioactivity of the Earth's surface, resulting from the presence of radioactive elements in the rocks and the emanation of radon, thoron and progeny, and (4) cosmic radiation having a significant impact on ionization of air in the atmosphere (Williams and Mareev, 2014).

In the case of the first group, radioactive substances were accumulated in the stratosphere (e.g., Alvarado et al., 2014), being a source of radioactive radiation related to GEC. For the second type of events, radioactive substances were released in the bottom troposphere and transported by movements of the air masses in the planetary boundary layer; the range can be determined as regional or local. In this group, one can also distinguish re-suspended radioactive dust and gamma rays from the ground fallout (Pierce, 1972; Yamauchi et al., 2012; Yamauchi, 2012). The third group is the local specificity of the measurement area associated with the geological structure of the Earth's crust.

Based on measurements of atmospheric electricity, meteorology, and air pollution carried out at the Geophysical Observatory at Świder during the above-mentioned events, the mechanism of the influence of high radioactivity on the parameters of atmospheric electricity is assessed. It may result from the phenomenon of inducing a surface charge (bound) due to changes in the ionosphere charge (and potential) or free and bound charge generation through a radioactive cloud, or air mass that overcomes the measurement site.

The induced charge arises as a result of electrostatic induction. The bound charge is related to the effect of the polarization vector (e.g., Griffiths, 2017). It is the charge accumulated on the surface conductor or dielectric. Any charge that is not a result of polarization (e.g., small ions in the atmosphere) is a free charge.

The ionization source generates free charges, which are measured by the Gardien counter, located in the proximity of the source. Radioactive cloud and aerosol can be detected from a considerable distance based on changes in the electric field (e.g., field mill, radioactive collector) and current (e.g., Wilson plate) near the Earth's surface (Israel, 1973b). These sensors work by measuring the induced (bonded) charge on a measuring electrode. According to Gauss's law, free and bound charges are the source of the electric field (e.g., Griffiths, 2017). The ionizing phenomena in the ground-level air which contribute to the atmospheric electricity are mainly related to the presence of radioactive substances of natural and anthropogenic origins.

An important factor is also the atmospheric radioactive fallout (i.e., precipitations and dry depositions) causing the transport and descents of radioactive substances to the surface of the earth. During of the Chernobyl nuclear power plant accident, the parameters of the atmospheric electricity reacted with rapid and sudden changes only when the air mass transported the radioactive material over Poland. During many years of testing

and using nuclear weapons, changes in the parameters of atmospheric electricity were recorded in the Świder Observatory.

In this discussion, one should also take into account the adaptation of the measurement technique, i.e., the selection of an appropriate sensor or the correct interpretation of the measured waveforms to assess the role of high radioactivity in the GEC.

The electric air conductivity is a product of the ion concentration (small, intermediate, and large), the ion mobility, and electric charge. The mobility of small ions is about three times that of large ions, hence (Chalmers, 1967) the small ions are mainly responsible for the conductivity in the air. Small ions are created by the ionization caused by the emanation of radioactive radon and thoron from the ground, and ionization by other radioactive elements in the air and by cosmic rays (Chamberline, 1991). The cosmic rays contain alpha particles (e.g., Mironova et al., 2015) that can be of great importance for the electric air conductivity.

The rate at which ions are produced at the Earth's surface is about 10 ion pairs of positive and negative in 1 cubic centimeter per 1 s (Israel, 1973a; Myslek-Laurikainen et al., 2011).

Blicard (1965) reports that when there is no strong radiation, α -rays have the greatest influence on air ionization a few meters from the ground surface (α -4.4, β -0.03, γ -0.15 ion pairs $\text{cm}^{-1}\text{s}^{-1}$). Radioactive substances in the surface soil mainly emit the γ (3.2 ion pairs $\text{cm}^{-1}\text{s}^{-1}$) and β (0.3 ion pairs $\text{cm}^{-1}\text{s}^{-1}$) radiation. Gamma radiation plays a significant role in the radiation from the ground (Blicard, 1965).

In the steady state and with a constant aerosol concentration, an increase in air ionization, e.g., as a result of a nuclear accident, causes an increase in the number of small ions. An increase in the aerosol concentration at a constant ion production causes a decrease in the ion concentration. The electric conductivity of the air is responsible for the support of conduction currents flowing in the Earth's atmosphere. The conduction current density, electric air conductivity, and atmospheric electric field are related by Ohm's law. The air conductivity, electric current density, and electric field are the main parameters of atmospheric electricity (AE).

According to the ionization equation (Chalmers, 1967, pp. 104–107), the small ion concentration in the surface layer depends mostly on the ion production and aerosol concentration.

Radioactive aerosol has specific properties: it is highly electrically charged. The process of attachment of radioactive substances to aerosol particles depends mainly on aerosol size, radioactivity decay rates, and mean free path of radioactive species in the atmosphere, and the electric field affects the mobility of the ions produced. Air ionization is a result of β and α emission and the formation of radioactive aerosol (Reed et al., 1977; Clement and Harrison, 2000; Tripathi and Harrison, 2003). Gamma radiation is also produced during the beta and alpha decay of radioactive substances. Cosmic rays and natural and cosmogenic radionuclides are air ionizing factors due to gamma emission. Small ions, especially in the situation of artificial radioactivity, can be produced as a result of simultaneous radiation of different types.

The radioactive elements carried into the atmosphere are due to the numerous natural and anthropogenic phenomena. Natural

are volcano eruption, radon and thoron exhalation from the ground, or radioactive dust particles coming as salt particles from the oceans or dust of radioactive rocks.

Since the discovery of radioactivity, the continuous increase of the number of pollution sources, like industrial use of radioactive materials or development of nuclear industry, fuel reprocessing, nuclear weapon tests in the air or underground explosions, and nuclear accidents (even if they have limited local range only) contribute to the registered electricity parameters.

The present study aims at explaining the role of artificial radioactivity in GEC using atmospheric electricity sensors and electrostatic analyzes. Simultaneous measurements of atmospheric electric parameters: electric field and air conductivity, radioactive fallout, precipitations, aerosol concentrations and meteorological parameters are presented. Variations of electric field and air conductivity in the presence of artificial ionization sources of various parameters are discussed. We proposed several scenarios of the atmosphere electric state, based on the relative locations of the ionization source.

Section “Instrumentation and Measurements” provides information on our instrumentations and measurement methods. Section “Analysis and Results” describes the electrical state of the atmosphere during global strong ionization incidents and analysis methods. Results are discussed and compiled in sections “Discussion” and “Conclusions.”

INSTRUMENTATION AND MEASUREMENTS

Atmospheric electricity parameters have been measured at the Geophysical Observatory at Świder, located in central Poland (52.12 N, 21.24 E) since 1958 (Kubicki et al., 2007).

The atmospheric air conductivity (positive and negative) at the Świder Observatory has been measured at 1 m over the surface with a Gardien counter. The critical mobility of the counter is $1.5 \times 10^{-4} \text{ m}^2 \text{ V}^{-1} \text{ s}^{-1}$. The density of the air-Earth electric current was measured by Wilson antenna with a 0.5 m² metal plate. Electric field E_z has been measured by a radioactive collector and rotating dipole field mill at a height of 2 m. The radioactive collector (the activity of about 30 μCi) is placed on a metal rod seated in a heated insulator. The height of the collector above the ground is 2 m. The time constant is 7 s. Comprehensive meteorological observations are also carried out (Kubicki et al., 2016).

The time resolution of atmospheric electricity measurements is now 1 s. At the time of the weapons tests and the Chernobyl accident, continuous measurements were recorded on a paper tape. The condensation nuclei in size range from $5 \times 10^{-9} \text{ m}$ to $1 \times 10^{-5} \text{ m}$ have been measured with a photoelectric condensation nuclei counter at 6, 12, and 18 UT.

From 2011 at the Świder Observatory the aerosol concentrations in the particle range from 3 nm to 3 μm were measured by ultra-fine condensation counter.

The atmospheric fallout is collected into a steel container with a surface of 0.5 m². The time of depositions is 1 week. For dry depositions, a container is rinsed several times with

distilled water, which then constitutes the measuring sample. The sample is vaporized and after the evaporation of water the damp remnant is transferred with the help of filter-paper and burned at a temperature not exceeding 500°C. To measure the global beta activity, the total ash mass is taken. Two Geiger-Müller (G-M) counters are used.

ANALYSIS AND RESULTS

Radon and Background Gamma Radiation in Świder Geophysical Observatory

The knowledge of the background radioactive radiation in the place where the electricity of the atmosphere is measured makes it possible to evaluate the global and regional effects.

Based on periodic measurements of the background of gamma and radon radiation, it can be stated that these values are small. The average value of radon concentration measured in May 2017 was 4.7 Bq m⁻³. No diurnal variability was noticed. The lack of radon variability was supported by the fact that the electric air conductivity measurements showed a minimum in the evening hours. The influence of radon after the decay of the mixed layer would increase the electric air conductivity.

The gamma background radiation from soil and atmosphere is on the level of $2.7 \times 10^{-6} \text{ R h}^{-1}$ (1970–1972) (Michnowski et al., 1976; Peňsko et al., 1976). In general, the radon potential in central and northern Poland is very low. There are fine-grained sands, tills and clays in the region of the Świder Observatory. The additional soil permeability is very low (Złotoszewska-Niedziałek, 2012).

The gamma background radiation originates mainly from rocks and soil. Cosmic radiation for gamma rays adds to ionization rate about 2 ion pairs cm⁻³s⁻¹ (Hoppel et al., 1986). Measurements in Świder Observatory do not indicate any significant correlation between gamma radiation dose rate and the electric field, air conductivity and concentrations of condensation nuclei (Peňsko et al., 1976). On the basis of 2 years of measurement of the background gamma radiation, a very low level was found. Short-term incidents of increased gamma radiation have been observed during heavy rain.

Relations between soil emitted γ -rays and the electric field have not been established by us, neither was it done in studies of Lopes et al. (2015) and Barbosa (2020).

Nuclear Weapons Testing

In the years 1958–1965, intensive tests on nuclear weapons were carried out at numerous places in the world. As a result, a significant portion of radioactive debris was injected into the upper troposphere and lower stratosphere. For many years this was a source of radioactivity with a changing intensity with time. The air layer at a height of 15–20 km was strongly ionized in the areas of nuclear weapons tests and a large area of the globe (Machta et al., 1962; Alvarado et al., 2014). One can distinguish two important physical mechanisms of transporting radioactive species to the surface of the earth; atmospheric turbulent mixing

in the planetary boundary layer and radioactive fallout at ground level (wet and dry contaminations deposited at ground level). Horizontal transport of radioactive species in the stratosphere is due to jet streams. Depending on the latitude, radioactive contamination can reach thousands kilometers away from the source. The global circulation of the atmosphere causes that the highest concentration of aerosol in the lower stratosphere occurs in low latitudes, and the radioactive material falls into the air at the middle latitudes, i.e., above 30 degrees (Seinfeld and Pandis, 2016). Radioactive pollutants are transported in the stratosphere where jet streams occur. Therefore, the Świder Observatory, due to its geographical location (52 N°), can monitor these processes.

The exchange of air between the stratosphere and troposphere is a slow process. The temperature gradient causes the radioactive molecules to coagulate to aerosol particles. From the theory of coagulation, it follows that the radioactive aerosol has a size of 15–500 nm (Reed et al., 1977; Tripathi and Harrison, 2003). The attachment of radioactive particles to the aerosol of different size and structure is an important physical process that influenced the further transport of radioactive substances to the troposphere and their removal. About 50% of the radioactive products were attached to aerosol particles with a diameter of more than 100 nm (Reed et al., 1977; Grundel and Porstendorfer, 2004). The fallout of a radioactive aerosol from the stratosphere to the troposphere was seasonal, with a maximum in spring due to rainfall.

Figure 1 shows the long-term variations in yearly average of: electric field E_z or potential gradient $PG = -E_z$, electric air conductivity λ_+ , radioactive fallout, aerosol (nuclei) concentrations, precipitation, and the number of thunderstorms. Long-term series of E_z measurements take into account the local measurement conditions related to the forest surroundings of the measurement site.

In the years 1958–1965/70, the field E_z was significantly lower (**Figure 1A**) compared to the long-term (1958–2000) average (216 Vm^{-1}). The annual changes of E_z were not that large ($100\text{--}150 \text{ Vm}^{-1}$), with large changes in electric air conductivity ($4\text{--}12 \times 10^{-15} \text{ Ohm}^{-1}\text{m}^{-1}$) (**Figure 1B**).

Radioactive fallout (**Figure 1C**) caused an increase in ground layer ionization. The generation of ions (free charge) has enhanced electric air conductivity. The precipitation (**Figure 1E**) compared to the aerosol concentrations (**Figure 1D**) was the main transport factor of the radioactive debris from the stratosphere to the ground level. Huzita (1969), reported an increase in ion generation due to an increase in the dry radioactive fallout component, based on observations in Osaka during 1960–1962. The geology of the local measurement site is also important in the analysis of the relationship between artificial air ionization and electric air conductivity.

The electric field E_z in 1958–1968 did not represent changes in the ionosphere potential (Markson, 2007) due to the strong ionization at the ground level. The electric charge at the ionosphere should be demonstrated due to induction in E_z at ground level. From 1968 the fallout was small and almost constant. Electric air conductivity is approximately constant because the additional ionization source (fallout) has ceased. This caused a partial increase in E_z (1968–1978/80) but at the same time E_z response to V_i changes resulting from radioactive

substances in the upper troposphere. The high level of air conductivity in the troposphere unlocked changes in the electric field E_z to induction through an electric charge and potential in the ionosphere. This appears to be a global effect, even if not supported by quantitative estimates.

Chernobyl Accident

On 1986 April 27 and 28 there was no cloud cover in the Świder Observatory. These were days with strong thermal convection. On the 26th of April 1986, a nuclear accident happened at about 01:23 UT in Chernobyl, Belarus, about 600 km from the Świder Observatory located in central Poland (52.12 N, 21.24 E).

On the next day, April 27, a sharp increase in the electric positive and negative conductivity was observed around 15 UT (**Figure 2**), and a maximum was reached at approximately 21 UT. During this period, the ground-level electric field significantly decreased and remained at a low level. The ratio of the positive to negative conductivity (**Figure 3**) was smaller than 1 (Warzecha, 1987). Similar effects have been observed in other locations over Europe (Israelsson and Knudsen, 1986; Sheftel et al., 1994). From April 27 to May 7 (**Table 1**) higher values of the electric air conductivity were observed at noon, due to convective exchange of the air and vertical transport of radioactive material from higher layers of the atmosphere to the ground. Due to the low wind speed and low dust concentration, the re-suspension of the radioactive material did not occur at that time. The mass of air contained very large amounts of radioactive elements: Cs-137, Cs-134, Sr-90, I-131, which emit β and γ radiation. This could be the reason for the change in the occurrence of a lower value of positive air conductivity as compared to the negative one, with their simultaneous increase (Sheftel et al., 1994). Such a situation has never been observed before. The increase in ionization causes a simultaneous increase in positive and negative air conductivity. Based on previous observations, the following changes in air conductivity can be distinguished. An increase in the aerosol concentration causes a simultaneous decrease in positive and negative air conductivity. During the occurrence of electrified clouds or precipitation, the changes in positive and negative air conductivity may have opposite directions.

During most of the days in May 1986, the variations of the electric field and air conductivity had large fluctuations in time and amplitude. Such a character of variations was absent before the accident. The average electric air conductivity in May 1986 was three times its normal May value (in 1981–1985), and the electric field in May 1986 was four times lower than the May average, and still three times lower than the average in August 1986 (Warzecha, 1991). These abnormal variations have been a result of the Chernobyl accident. The atmospheric electricity at Świder Observatory began returning to its pre-accident values in September 1986 (Kubicki et al., 2013).

The air mass containing radioactive substances passed over the measuring site around 19 UT (**Figure 2**). A simultaneous increase in the positive and negative electrical air conductivity indicates the presence of ionization sources. Free electric charges have been generated. The field dropped below 100 Vm^{-1} . At the time of the Chernobyl accident, the main factor affecting the atmospheric

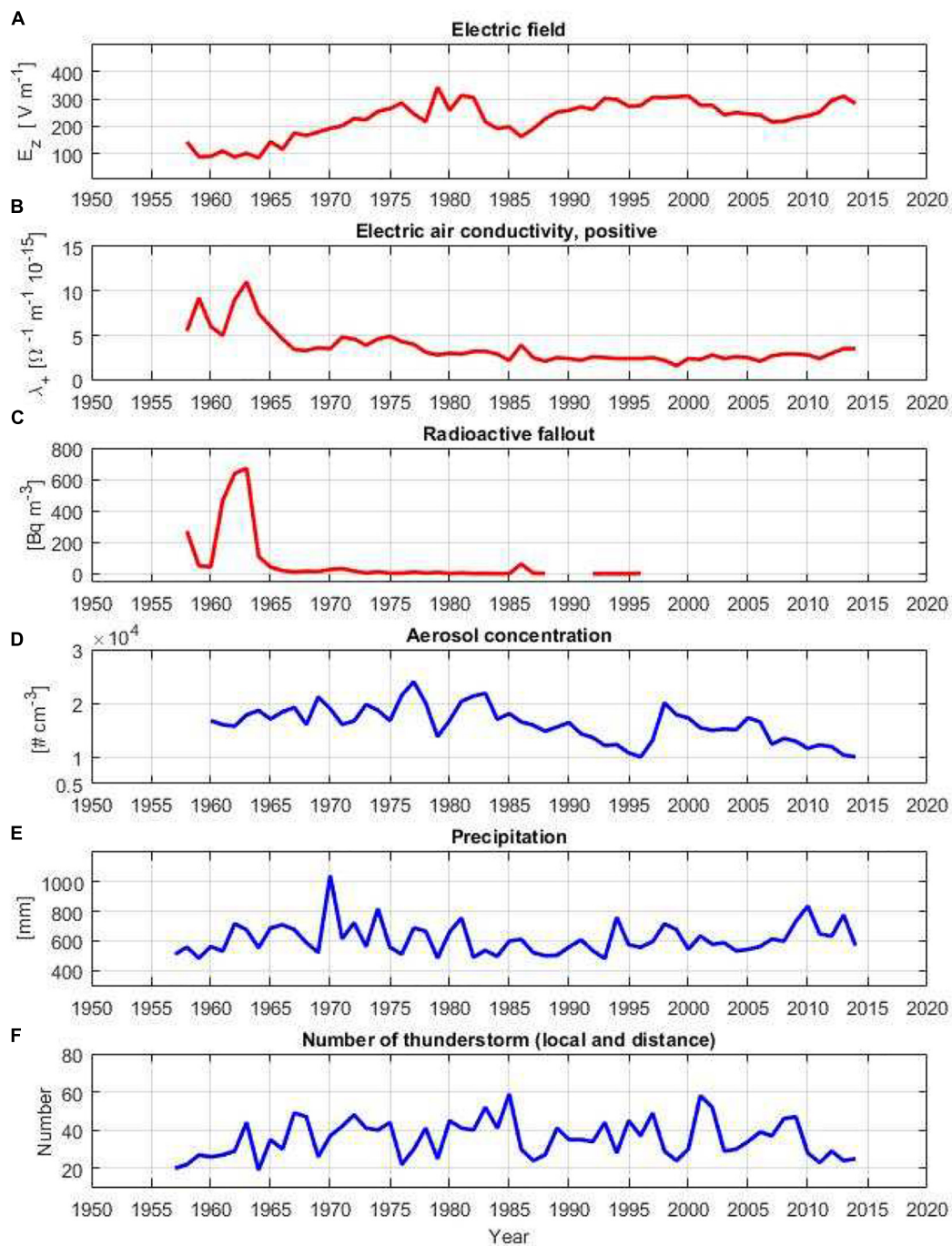


FIGURE 1 | Long term (1958–2014) variations: **(A)** electric field E_z or potential gradient ($PG = -E_z$), **(B)** electric air conductivity λ_+ , **(C)** radioactive fallout, **(D)** aerosol concentrations, **(E)** precipitation, **(F)** number of thunderstorms. We use the convention that the downward directed, i.e., fair weather, atmospheric electric field is positive (z -axis is directed downward) (Krehbiel et al., 2014).

electricity is not the precipitation but the presence of a strong ionization source in dry contamination of air.

An interesting incident was the occurrence of the distant thunderstorm on April 30, when the ground surface ionization was very strong. Electric field registration showed the occurrence of lightning discharges. Low time recording resolution,

appropriate for fair weather measurements (paper tape speed) did not allow for the analysis of the nature of the discharges and the electrical structure of the thundercloud to determine a possible influence of the high air conductivity of the surface layer. Nuclear lightning issues have been widely discussed, e.g., by Williams et al. (1988).

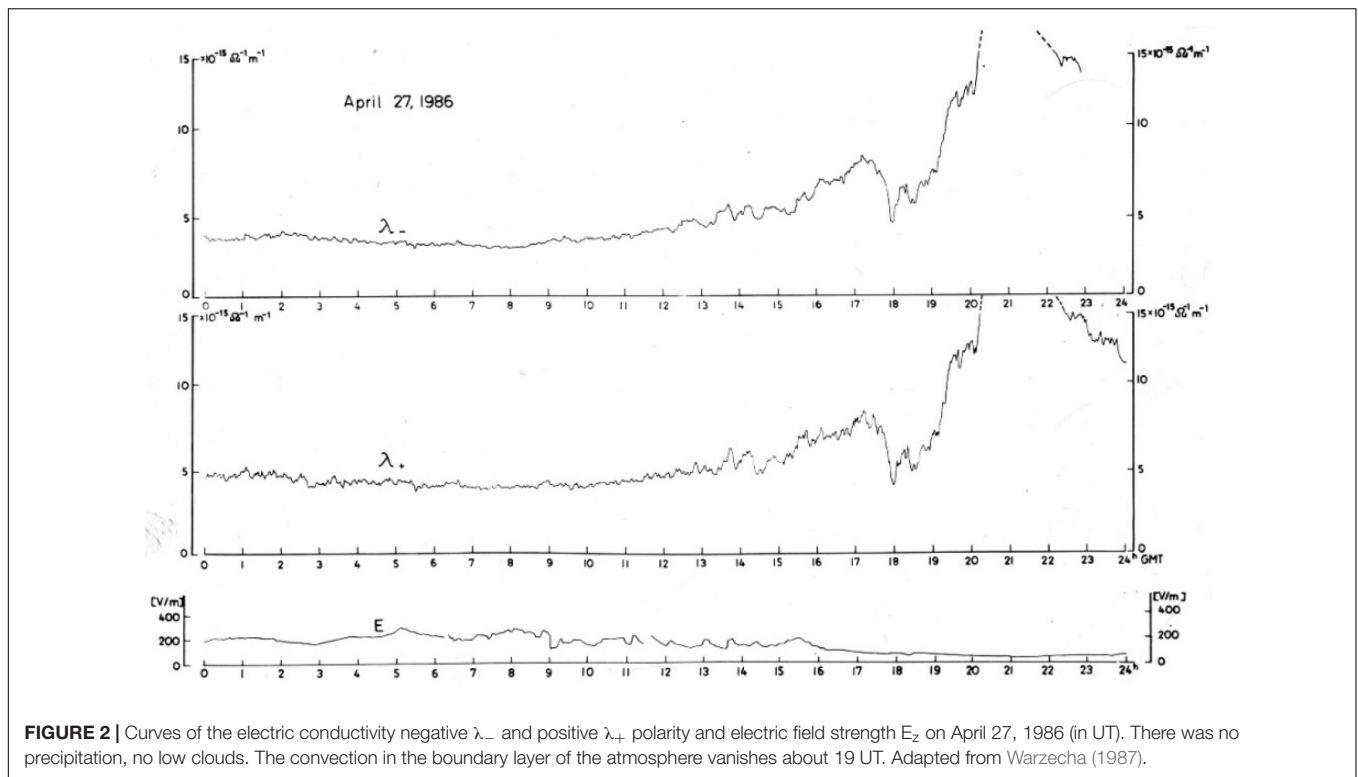


FIGURE 2 | Curves of the electric conductivity negative λ_{-} and positive λ_{+} polarity and electric field strength E_z on April 27, 1986 (in UT). There was no precipitation, no low clouds. The convection in the boundary layer of the atmosphere vanishes about 19 UT. Adapted from Warzecha (1987).

Fukushima Accident

The nuclear accident in Fukushima, Japan, happened on 12 March 2011 as a result of damage by a 9.0 earthquake and tsunami (Newsletter on Atmospheric Electricity, 2011). **Figure 4** shows the trajectories of air masses that reached Poland on March 22 and 23. The Polish National Central Laboratory for Radiological Protection (CLOR)¹, informed that the radioactive material arrived over Poland on 23 March and the level of concentrations of some radioactive isotopes was insignificantly increasing until 1st April and then their level decreased rapidly. The detailed situation in Europe has been presented e.g., by Bossewa et al. (2012); Kirchner et al. (2012).

By the end of March, Fukushima radionuclides have been identified in various locations in the Northern Hemisphere, but they did not significantly affect the electrical parameters of the atmosphere measured in remote locations (Comprehensive Nuclear-Test-Ban Treaty Organization [CTBTO], 2011; Dragović et al., 2020). In Poland, the concentration of radionuclides was very low. I-131 was detected, its concentration being around several hundred $\mu\text{Bq m}^{-3}$. The backward trajectories were calculated for heights of 0, 1, and 5 km (**Figure 4**) and 1.5, 2, 4 km (not presented). On this basis, it can be concluded that on March 22–23, air masses on an altitude of 4–5 km from the regions of Fukushima reached the Świder Observatory at an altitude of 1–4 km. The air mass came into the planetary boundary layer. At that time, the influence of radioactive contaminations on the atmospheric electricity was possible.

¹www.clor.waw.pl

Indeed, significant effects of radiations on atmospheric electricity have been observed at Kakioka, Japan (Takeda et al., 2011; Dragović et al., 2020). A reliable estimate of such effects requires atmospheric electricity parameters observed during fair weather.

There were more than 10 fair weather days in March 2011 at the Świder Observatory, seven before the accident (1–4, 7, 9, 11) and seven after the accident (12, 21, 22, 23, 27, 30, and 31).

The fair weather conditions used in our analysis mean there is no rain, drizzle, snow, hail, fog, no local or distant thunderstorms, the lower cloudiness is less than 4/8 (8/8 is overcast), and when the wind velocity is less than 6 m/s, the electric field value was not negative (Kubicki et al., 2016). Additionally, fair weather days were selected in terms of eliminating the influence of aerosol. This criterion concerned: aerosol concentration ($<20\text{--}25 \times 10^3$ particles cm^{-3}), electric field strength ($<1,000$ Vm^{-1}), analysis of simultaneous variability of electric field and air conductivity.

The daily averages of the field observed on all fair weather days in March 2011 are shown in **Figure 5**. The days with very low aerosol concentration were selected. The E_z data have been normalized (blue line) to the values of the daily average, to select artifacts caused by the Fukushima accident.

Diurnal variations of the electric field and the positive and negative air conductivity observed at Świder Observatory on fair weather days, 22nd and 23rd of March, when radioactive air masses reached Poland are shown in **Figures 6, 7**.

Long-term average of positive conductivity of March is 2.44×10^{-15} $\text{Ohm}^{-1}\text{m}^{-1}$ (std, 0.97) and for April it is 3.16×10^{-15} $\text{Ohm}^{-1}\text{m}^{-1}$ (std, 1.39). In 2011, the air

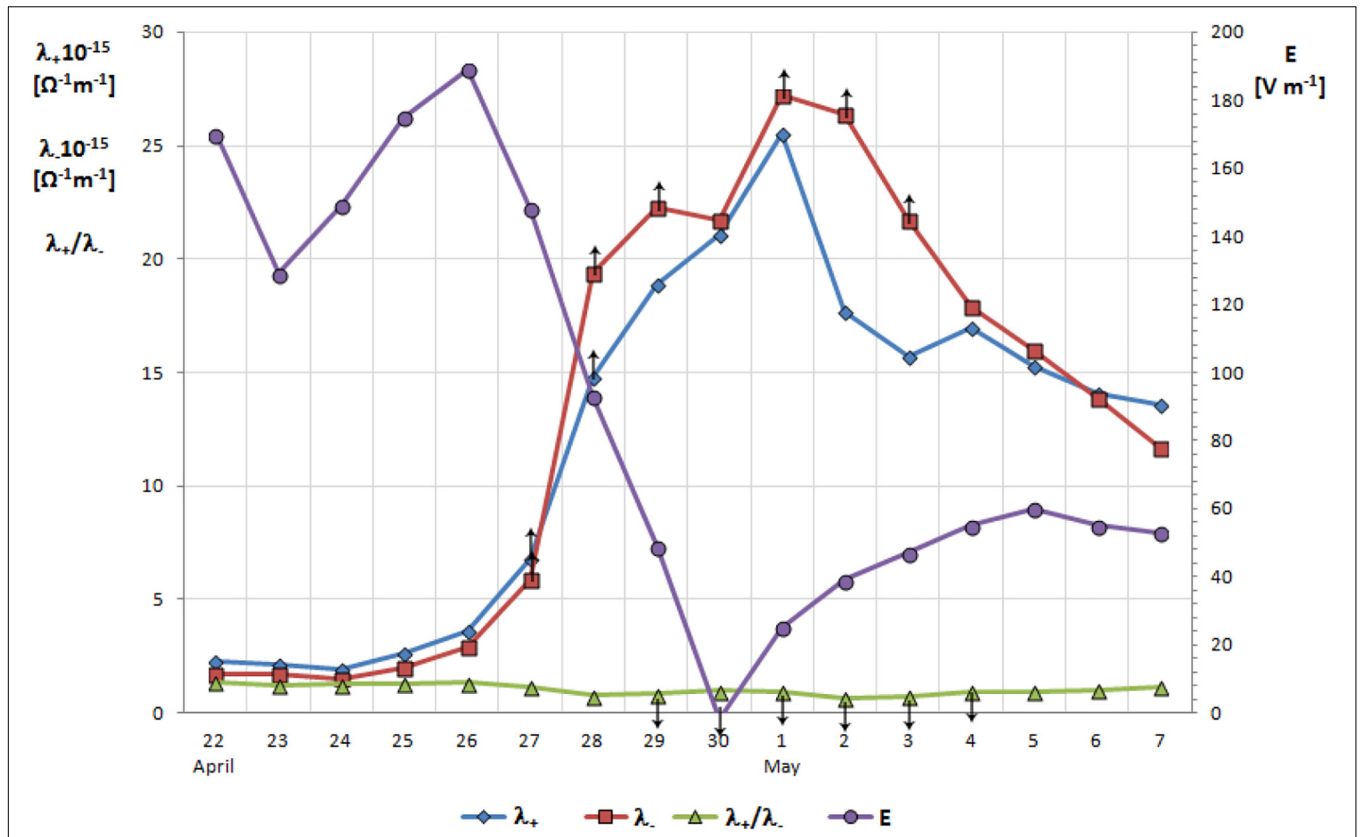
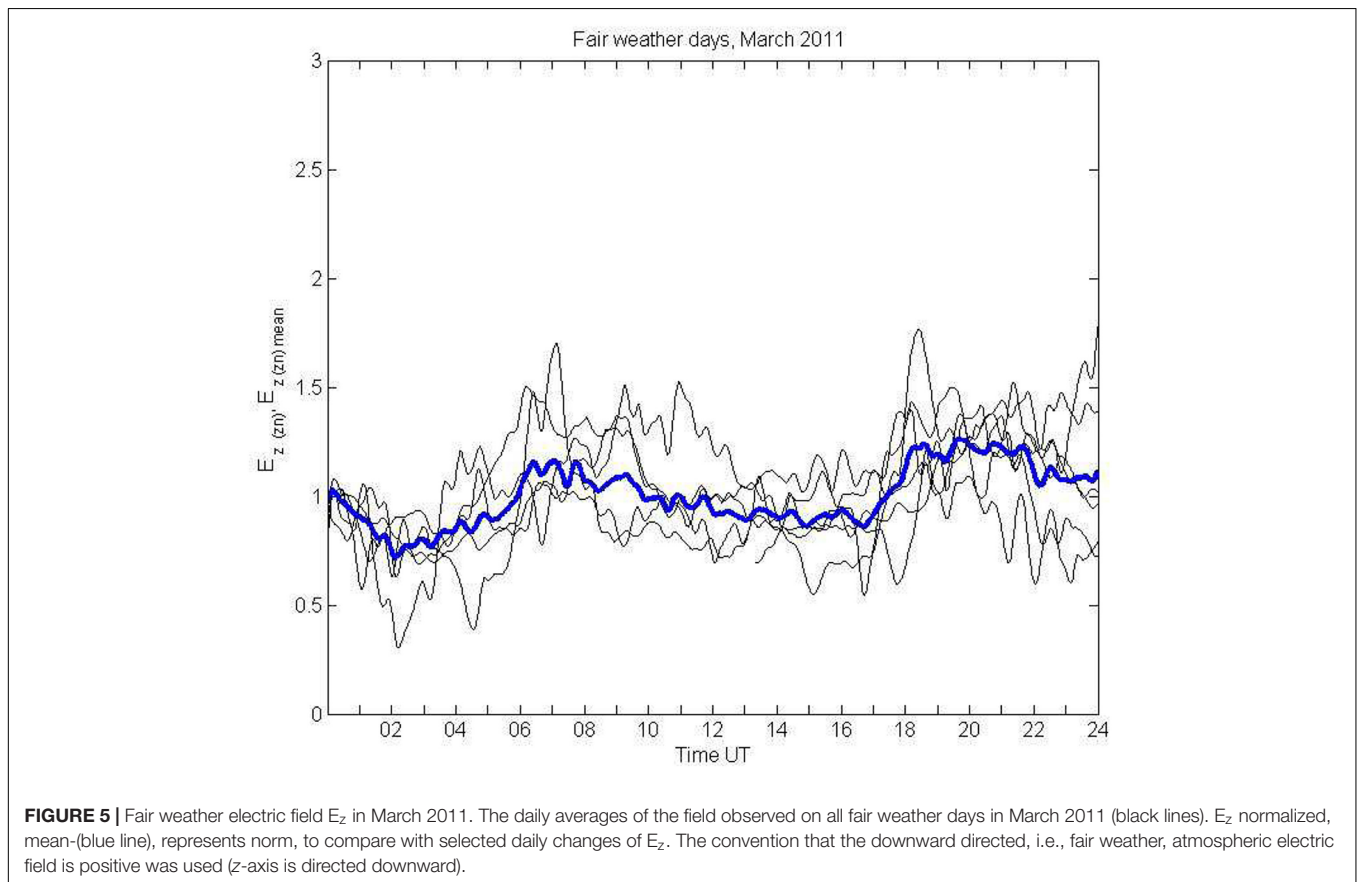
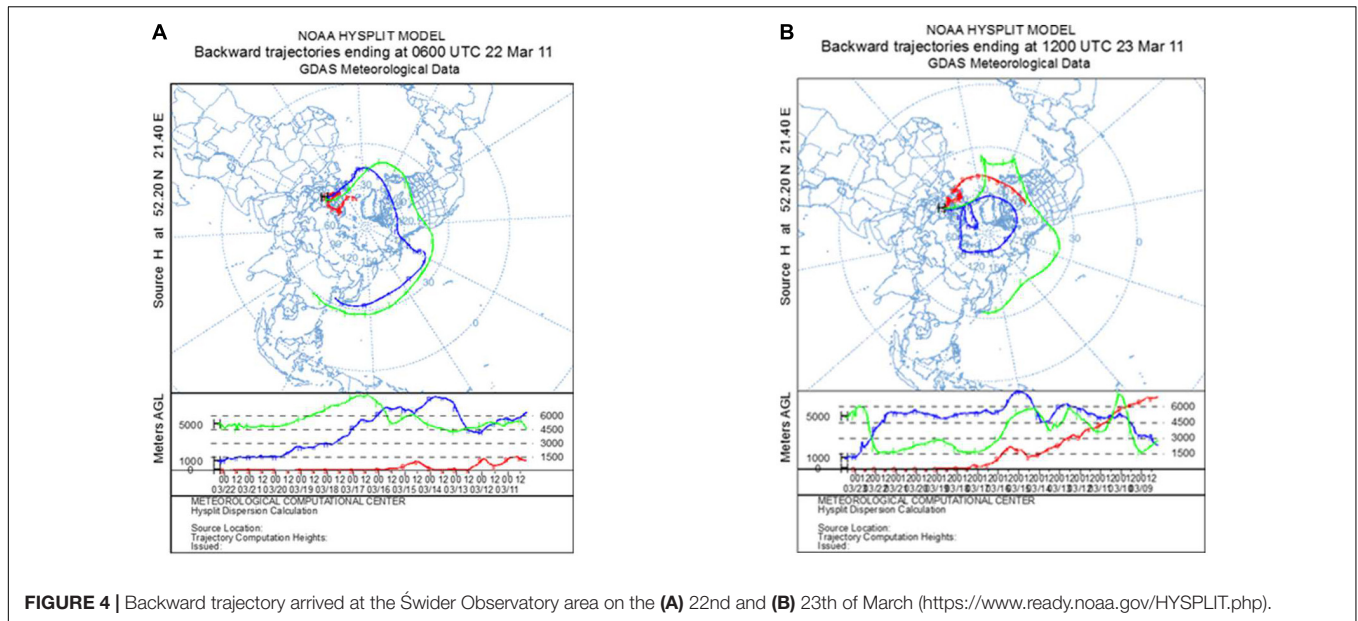


FIGURE 3 | Electric field E_z , positive λ_+ and negative λ_- air conductivity and ratio λ_+/λ_- from 22 April to 7 May 1986 measured in Świdler Observatory. Daily average values are presented. The arrows indicate that the real value was greater than the presented value. It results from the adopted average method for measurement data processing in a situation where the course of the measured parameter was greater (for a time less than 20 min) than the range of the measuring instrument.

TABLE 1 | Daily values of electric parameters and meteorological observations from April 22 through May 7, 1986, at Świdler Observatory: λ_+ – positive electric air conductivity, λ_- – negative electric air conductivity, E_z – electric field strength, N – number of concentration nuclei, D – air dust; S – cloudiness; C – type of clouds; Ws – wind speed; P – precipitation.

Date 1986	$\lambda_+ \cdot 10^{-15} [ohm^{-1}m^{-1}]$	$\lambda_- \cdot 10^{-15} [ohm^{-1}m^{-1}]$	$E_z [V m^{-1}]$	N $10^3 [cm^{-3}]$	D $[mg m^{-3}]$	S [0-10]	C	Ws $[ms^{-1}]$	P [mm]
April 22	2.3	1.7	170	37.9	0.020	2.7	Ci	2.0	.
23	2.1	1.7	129	55.3	0.054	4.0	Ci	2.0	.
24	1.9	1.5	149	27.7	0.062	4.0	Ci, Cu	1.7	.
25	2.6	2.0	175	26.0	0.018	5.0	Cu, Ci, Ac	3.0	.
26	3.6	2.9	189	17.6	0.011	5.3	Ci	4.0	.
27	>6.8	>5.9	148	11.7	0.016	1.0	Ci, Cc	3.3	.
28	>14.8	>19.4	93	13.0	0.074	0.0	.	1.3	.
29	18.9	>22.3	49	10.6	0.037	1.7	Cu	2.0	.
30	21.1	21.7	<-2	11.9	0.008	4.0	Cu, Ac	1.7	0.0
May 1	25.5	>27.2	25	7.0	0.015	3.3	Cu, Ci	1.7	.
2	17.7	>26.4	39	19.4	0.024	0.0	.	2.0	.
3	15.7	>21.7	47	15.4	0.019	0.3	Cu	1.3	.
4	17.0	17.9	55	11.8	0.012	0.3	Ac, Ci	2.7	.
5	15.3	16.0	60	14.6	0.013	0.0	.	2.3	.
6	14.1	13.9	55	14.5	0.009	2.3	Cu, Ci	2.7	.
7	13.6	11.7	53	18.7	0.019	0.3	Ci	2.7	.

The dust D (PM, particulate matter, the mixture of solid particles and liquid droplets suspended in air) was measured by the reference method. The following cloud type classification was used: Cu, cumulus; Ac, altocumulus; Ci, cirrus; Cc, cirrocumulus.

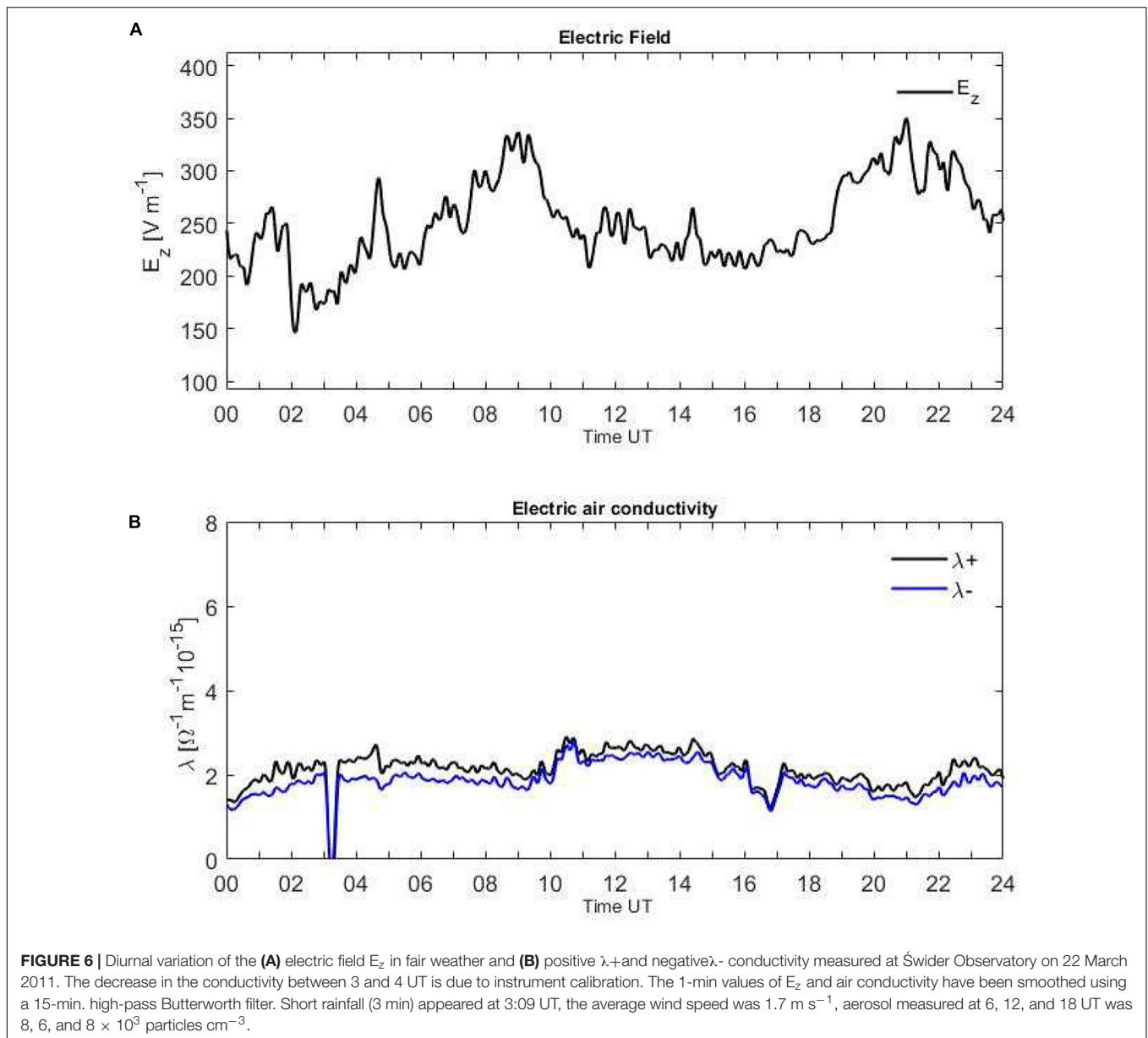


conductivity averages for March and April were 1.79 and $2.5 \times 10^{-15} \text{ Ohm}^{-1}\text{m}^{-1}$, respectively.

Long term average (1965–2000) of electric field of March is 300 Vm^{-1} (std, 85 Vm^{-1}), and for April it is 217 Vm^{-1} (std, 61 Vm^{-1}) (Kubicki et al., 2007). In 2011, the electric field averages

for March and April were 320 and 231 Vm^{-1} , respectively. All monthly averages given above have been calculated for fair weather conditions.

On the basis of the presented values of positive electric air conductivity and electric field intensity it can be stated that the



Fukushima accident was not reflected in the monthly statistics recorded at the Świder Observatory. Diurnal variation of the electric field E_z and air conductivity were also not disturbed (Figures 6, 7).

After the Chernobyl incident, the elevated monthly averages continued for 3 months and caused an increase in the annual average value in 1986 in comparison with the previous year, i.e., 1985 and the next year 1987 (Figure 1).

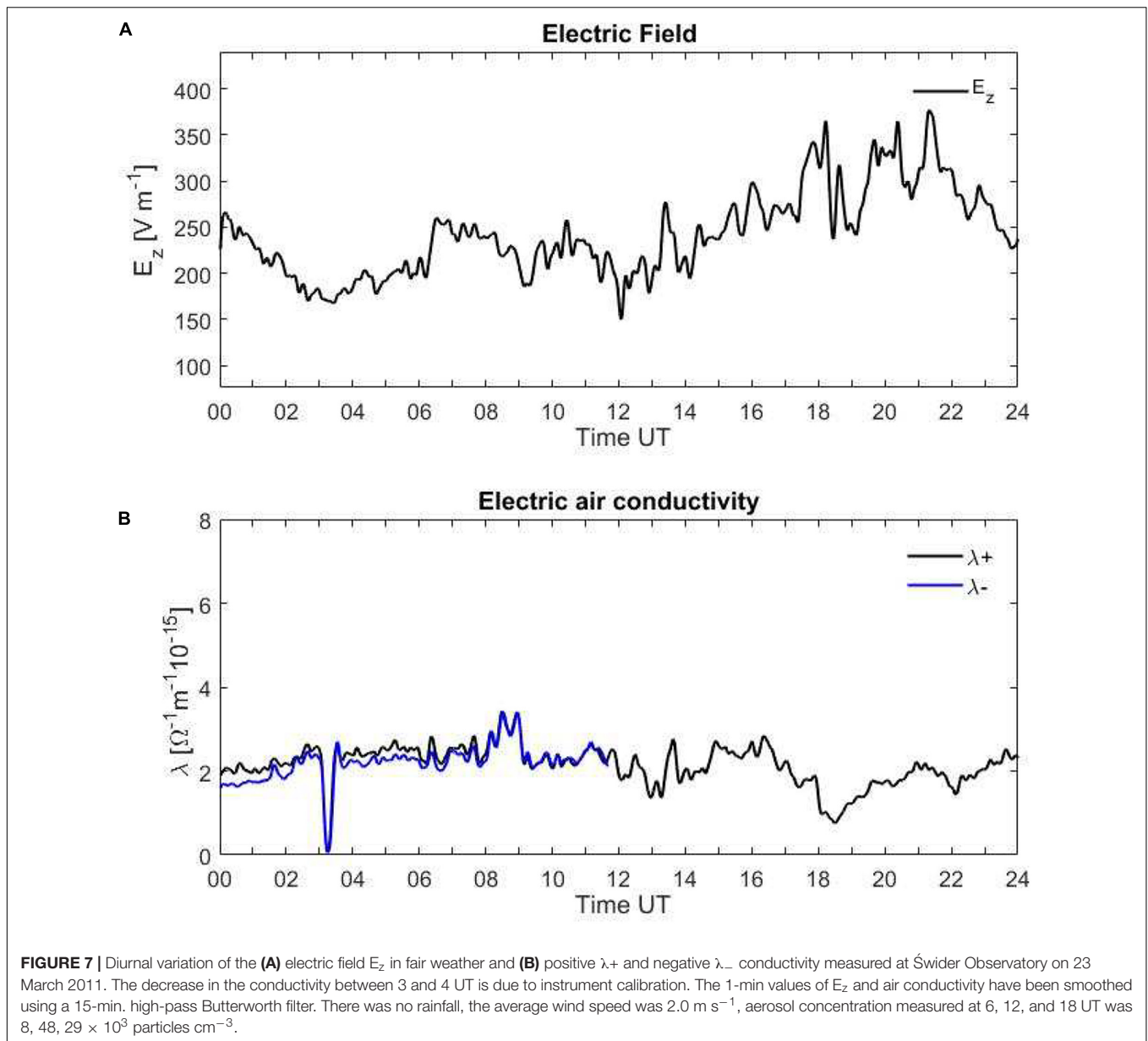
Based on the report of the Central Laboratory for Radiological Protection in Warsaw, it can be concluded that recorded concentrations of radioactive debris in Poland were tens of thousands times lower in Fukushima than in the Chernobyl accident (see text footnote 1).

The Fukushima accident did not affect the fair weather atmospheric electricity parameters measured at the ground

surface at the Świder Observatory, despite the presence of a small concentration of radioactive substances.

DISCUSSION

Small positive and negative ions are the main factor determining the electrical conductivity of air. Alpha, beta, and gamma rays can produce ion-pairs. In situations of artificially increased radiation, radioactive electric charging of aerosols occurs (Clement and Harrison, 1992). Radioactive pollutants are ionizing the air primarily through beta and indirectly gamma decays. The most efficient radioactive sources that affect the electric air conductivity are radioactive elements that emit alpha radiation, e.g., Am-241 and Ra-226. Due to their size, energy and



electric charge, the alpha particles can be considered an important source of air ionization (e.g., Seran et al., 2017). They induce a significant increase in the electrical conductivity of air but are unlikely to be a component of artificial radioactive releases.

Negative ions have higher mobility than positive ions (Gunn, 1954). The beta minus radiation that occurred during the Chernobyl incident could have caused a significant increase in the concentration of negative small ions compared to positive small ions. As a result, the negative electric air conductivity was greater than the positive air conductivity (Figure 3).

Charged aerosol through electrostatic interactions can influence microphysical processes in clouds and air (e.g., Clement and Harrison, 1995). The most important parameters that represent the cloud or radioactive aerosol are: particle concentrations and size, type of ionizing radiation, disintegration

rate and height of the cloud base, particle properties and cloud lifetime. The charging mechanism of radioactive cloud or radioactive aerosol particles is very complicated (e.g., Greenfield, 1956; Reed et al., 1977; Clement and Harrison, 1995).

The presence of a radioactive cloud or aerosol is associated with the formation of a region of very high electric air conductivity in a less conductive atmosphere. However, the space charge of the radioactive cloud or air mass may be zero (Holzer, 1972; Greenfield, 1956), and the electric field and air conductivity changes in the lower atmosphere may also be insignificant (Harris, 1955). In a long time (several minutes), the electric charge is not accumulated in the radioactive cloud or air mass. There is also no separation of positive and negative electric charges. The electric dipole (negative charge on top) moment in the cloud is very small and occurs for a few minutes.

During this time perturbations of the air–Earth current may occur (Holzer, 1972).

Depending on the location of the ionizing radiation source in relation to the measuring sensors, several classes of the description of ionizing radiation impact on electric field, current and electric air conductivity measured at the earth's surface can be distinguished:

1. The ionization source is located at the atmospheric electricity measuring site or a short distance from it. The mechanism of interaction of radioactive substances is based on the direct ionization of the ground layer in which the sensors are located. Small ions are produced, radioactive particles attach to the aerosol particles, and a free electrical charge is created. The precipitation causes the radioactive substance to be transported to the ground surface, and locally significantly affects the parameters of the atmospheric electricity. This is presented on long-term courses in 1960–1967 (**Figure 1**).
2. The radiation source is initially located at a considerable distance from the measuring site. There is a cloud of radioactive aerosol moving with air masses. A space charge associated with a mass of cloud or an aerosol may cause a change in the electric field at ground level due to electrostatic induction (bound charge) in distant site measurements. This mechanism can be similar, e.g., to the changes in the electric field as a thunderstorm and electrified cloud [e.g., *cumulonimbus* (Cb), *nimbostratus* (Ns), *stratus* (St)] approaches. The influence of a radioactive source on the electric air conductivity is detected when small ions (free charge) reach the Gardien counter.

Based on the measurements on 27 April 1986 (Chernobyl accident), it can be concluded that the approaching radioactive aerosol had its signal in the course of the electric field from about 09 UT (**Figure 2**). The E_z fluctuations may indicate a change in the space charge of a moving air mass. Between 15 and 16 UT, the cloud already covered the measurement site at the Świder Observatory, E_z dropped significantly and remained at a low level for the next several hours. The appearance of the air mass has been well detected by E_z . Radioactive fallout (dry depositions) by mixing the atmosphere will increase the electric air conductivity in air column.

The electric field was very small and remained in this state even after the cloud had passed. Increasing ionization in the entire boundary layer of the atmosphere (e.g., 0–2,000 m) increases the electric air conductivity and significantly reduces the column resistance (unit resistance column of air). The resistance of the 2 km high air column is 60% of that of the earth-ionosphere air column (e.g., Chalmers, 1967). The ionized air layer reduced the electric field (was a short circuit).

Radioactive contaminations can affect the E_z distribution in fair weather areas. Around 17 UT, April 27 (**Figure 2**), there was a significant decrease followed by an increase in the electric air conductivity, probably caused by an increase in aerosol concentration (at 18 UT it was 20.4×10^3 particles cm^{-3} , while at 12 UT it was 9.8×10^3 particles cm^{-3}), the decline of vertical air

mixing, and perhaps also a change in the wind direction from SSE to ESE. The aerosol in comparison with ionization as the main factor producing changes in the electrical air conductivity.

From 09 to 16 UT the relationship between E_z and λ it was not inversely proportional. A similar mechanism was described by Holzer (1972) during nuclear explosions.

3. The ionizing source is located very high, i.e., on the border of the troposphere and the stratosphere, in areas of high air conductivity. Also, this conductivity has been significantly increased by the presence of radioactive substances. This probably caused an increase in the electric charge and the potential V_i of the higher layers, i.e., the ionosphere. Markson (2007) shows that the increase of V_i was due to nuclear weapons testing. The V_i change did not manifest itself in the electric field E_z (**Figure 1A**) in an annual time scale. The main reason for the increase in V_i was the enhancement in global thunderstorm activity and an increase in the electric current between the top of the thunderstorm cloud and the ionosphere (Markson, 2007). Radioactive fallout increased the conductivity at the ground level, causing E_z to fall. The presence of two highly conductive air layers (separated by a layer of small conductivity) in the upper troposphere and surface layer may have caused the GEC to be not synchronized, i.e., global V_i and E_z in the Świder Observatory have not corresponded to each other. A detailed description of the presented dependencies would require the use of modeling for the establishment of a vertical air conductivity profile for nuclear weapons testing.

During movement of the contaminated air mass in the form of an aerosol or a cloud to the measuring site, the induced charge in the measuring sensor of the electric field or current density (field mill, Wilson antenna) will appear earlier than the ions (free charge) represented by the electric air conductivity and measured by a Gardien counter.

At the time of the Chernobyl accident, when the air mass of radioactive substances with advection transport reached the vicinity of the Świder Observatory, it caused a mild increase in electric air conductivity and a decrease in the electric field. There was no rain, and strong vertical turbulent exchange disappeared in the evening. Maximum values of conductivity were reached between 21 and 22 UT when the vertical turbulent air exchange vanishes. On this basis, it can be concluded that the radioactive aerosol has generated small ions in the entire planetary boundary layer. The forming stable boundary could additionally increase the concentration of small ions at the earth's surface. The ionization source was the homogeneous air mass with significant space dimensions; therefore, the electric field did not have a spike that had been described by Yamauchi et al. (2012).

The resultant electrical structure of the cloud with the radioactive material should not show any separation areas of electric charges. Analyzing the ionization mechanism for this case, it can be concluded that the electrification processes are intermittent and last very short compared to the disintegration rate (Greenfield, 1956). Based on measurements of the electric field near the ground, it is possible to detect the front of

a radioactive cloud or aerosol air mass. If the air-Earth current measurements were carried out, one would expect bipolar pulses related to the time change in space charge radioactive cloud. The model of the radioactive cloud or aerosol with polarized electric charges (positive at the top, negative at the bottom) was proposed by Yamauchi et al. (2018) to analyze spikes in the course of an electric field during the Fukushima accident. During nuclear explosions, nuclear lightning can occur on the electric charge distribution in a strong electric field (Holzer, 1972; Williams et al., 1988). There may be a negative charge at the top of the thundercloud (Holzer, 1972), unlike the proposed model of Yamauchi et al. (2018).

When considering air ionization processes, the role of atmospheric aerosol should be taken into account. The condensation nuclei CN measured in the Świder Observatory include solid and liquid particles; gas form was not detected. The concentration nuclei during nuclear tests changed little in the years 1960–1965 and amounted to about 20×10^3 particles cm^{-3} . At the time of the Chernobyl accident, the concentration of condensation nuclei between April 25 and May 7 varied from 26 to 19×10^3 particles cm^{-3} . The effect of the aerosol on the electric field and air conductivity was not significant (Figure 3), as its concentration has not exceeded the critical value.

Radioactive substances attach to small aerosol particles, <500 nm (Tripathi and Harrison, 2003). Based on the measurements of the aerosol concentration, it can be concluded that there was no important increase in the number of condensation nuclei.

From 1986 April 27 to May 7 there was no precipitation, no low-level cloud, the wind was low, $1\text{--}3$ ms^{-1} . The radioactivity contaminated aerosol was transported to the surface level in turbulent mixing. Particle re-suspension was rather absent, due to the low wind speed and the small dust concentration. On May 1–3, the electric air conductivity was maximum ($15\text{--}27 \times 10^{-15}$ $\text{Ohm}^{-1}\text{m}^{-1}$) and E_z was very low, $25\text{--}47$ Vm^{-1} . The aerosol concentration was $7\text{--}20 \times 10^3$ cm^{-3} . Ionization of the ground level would be much higher if atmospheric precipitation occurred. The ion effect on aerosol formation with nuclei is complicated for the high ionization conditions. Pulnests (2009) suggested that the ionization enhancement first increases ion concentrations but after several days it activates to increase small-size aerosol and decreases the electric air conductivity. This physical mechanism was not confirmed based on measurements carried out at the Świder Geophysical Observatory.

Enhanced conductivity in the upper troposphere and stratosphere as a result of a nuclear test, caused an increase of ionosphere potential, V_i . Markson (2007) reported the enhancement of ionosphere potential V_i by approximately 40% in the 1960–1965 period in nuclear weapons testing. The measured values of V_i have achieved maximum, 500 kV. By 1966, V_i has decreased to the value before nuclear testing and changed $\pm 10\%$ of the mean.

Markson (2007) suggested that the enhanced lightning activity due to increased ionization in the upper troposphere

and stratosphere caused enhanced GEC source current between upper thundercloud and the ionosphere. Israelsson et al. (1987) has not reported an increased occurrence of lightning flashes in Sweden after the Chernobyl accident. The number of thunderstorms in the Świder Observatory in 1960–1967 is shown in Figure 1F. The maximum number of thunderstorms occurred in the same years (1962–1963) as the maximum of radioactive fallout. Finding a physical connection between the increased thunderstorm activity in 1963 and the radioactive fallout, would require additional studies on a monthly time scale, including comprehensive meteorological data.

The role of high ionization in the formation of atmospheric discharges was analyzed by Israelsson et al. (1987), and Williams et al. (1988). Indeed, the enhanced GEC source current could elevate the value of ionospheric potential and also enhance the lightning activity.

The global reach of the nuclear tests, Chernobyl, and Fukushima accident, is difficult to establish based on measurements in one location. However, it is possible to analyze the mechanism of the interaction of radioactive substances on the electrical state of the atmosphere. Nuclear testing could be considered a global phenomenon due to the location of the source of the radioactive substances in the stratosphere.

Related to natural ionization, the impact of these incidents may only be significant in some sites around the globe (e.g., Hoppel et al., 1986; Harrison et al., 2020).

It should also be noted that the interpretation of the parameters of atmospheric electricity based on direct measurements nearby a strong ionization source zone can be very difficult (e.g., accident in Fukushima, highly ionized air mass at the Świder Observatory). The application of Ohm's law may be limited due to the non-linear electrical properties of the atmosphere.

CONCLUSION

In the analysis of the mechanism of interaction of high radioactive contamination with the atmospheric electricity, parameters of the ionization source and its location in relation to the measuring site play an important role. The formation and charging of radioactive aerosols is an important issue for the presented studies. The properties of the aerosol at the measurement site may modify the level of air ionization and electricity.

The particles of the radioactive aerosol can have a significant electric charge. The beta and gamma radiation produced by radioactive substances generates most of the space charge in the form of small ions (free charge). The most effective transport of radioactive substances to the earth's surface is provided by atmospheric precipitation (wet component of radioactive fallout).

Relations between V_i and E_z for the conditions of occurrence of highly ionized layer at the ground level (due to radioactive

fallout) and the border of the atmosphere and stratosphere (the case nuclear tests) require studies using models. Measurements of atmospheric electricity parameters E_z and λ are necessary and air-Earth current J_z is also useful to analyze the impact of air radioactivity during significant incidents (accident, nuclear tests, nuclear power failures, and release from fuel reprocessing plants), as these parameters allow a comprehensive electrostatic interpretation.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

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AUTHOR CONTRIBUTIONS

MK contributed to the data processing, data curation and data analysis, and manuscript writing. BM-L and AO contributed to the data analysis and manuscript writing. All authors equally cooperated in the research presented in this publication.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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