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# Influences of cosmic radiation, artificial radioactivity and aerosol concentration upon the fair-weather atmospheric electric field in Lisbon (1955–1991)

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**Abstract**

The atmospheric electric field is influenced by cosmic radiation, radioactivity and aerosols. In this work we investigate the existence of: (i) correlations between relative anomalies of annual values of atmospheric electric field and cosmic radiation intensity, artificial radioactivity and aerosol concentration; (ii) seasonal correlations between relative anomalies of the atmospheric electric field and cosmic radiation intensity. We used data of the electric field strength recorded at the Portela meteorological station (Lisbon) in the period 1955–1991. We found statistically significant inverse correlations between atmospheric electric field and cosmic radiation in the period 1967–1991. We also found that the influence of cosmic radiation on the atmospheric electric field is strong in wintertime and very weak in summertime. The GCR–CN–CCN–Cloud Hypothesis and the wintertime reduced boundary layer convection are analyzed as possible explanations for this difference.


*Keywords:* Fair-weather electric field; Cosmic radiation; Radioactivity; Aerosol concentration

## 1. Introduction

It has been long recognized that cosmic radiation, artificial radioactivity and volcanic eruptions are long period influences on the atmospheric field strength. In fair-weather conditions

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(Voeikov, 1965), and assuming weak boundary layer convection, the vertical component of the atmospheric electric field at ground level $E_z$, induces an almost ohmic current density $J_z$, given by

$$J_z = \sigma E_z \tag{1}$$

where $\sigma$ is the electric conductivity of the air (see for example McGorman and Rust, 1998). As the fair-weather current density is nearly constant, the field strength varies inversely with the electric conductivity of the air, which depends on the concentration and mobility of the atmospheric ions. Actually, the electric conductivity is related to the ion concentration $n$, electric charge $q$, and mobility $\mu$, through:

$$\sigma = n_+ q_+ \mu_+ + n_- q_- \mu_- \tag{2}$$

where the subscripts + and − refer to positive and negative charges, respectively.

From Eqs. (1) and (2), we observe that the product of ion density to ion mobility practically determines the fair-weather electric field strength.

Ion density depends upon a variety of factors. Solar radiation, artificial radioactivity and cosmic radiation definitely are major ion sources in the atmosphere. Solar radiation generates ions during daytime especially in the electrosphere, i.e. the outermost layer of the atmosphere. Artificial radioactivity, which comes mainly from nuclear blasts in the atmosphere during the late fifties, generates ions in the boundary layer, namely up to 1 km height. Cosmic radiation acts directly upon the electric field over all the atmosphere levels (see for example Harrison and Carslaw, 2003), while mediating water vapor nucleation on aerosols in the boundary layer.

Ion mobility is lowered through water vapor nucleation on ions, followed by hygroscopic growth and through ion attachment to coarse aerosol particles, namely those that result from volcanic emissions, combustion and dust re-suspension. In recent years, mechanisms for explaining mediation of water vapor nucleation by cosmic radiation have been proposed, namely by Svensmark and Friis-Christensen (1997), Marsh and Svensmark (2000a,b), Harrison (2000), Kirkby and Laaksonen (2000), Yu and Turco, (2000, 2001). The two main mechanisms proposed are the following (Carslaw et al., 2002): (i) *ion-aerosol clear-air mechanism*; and (ii) *ion-aerosol near-cloud mechanism*.

The ion-aerosol clear-air mechanism is based on the idea that the ions could aggregate other particles and grow into cloud condensation nuclei (CCN) which offer a lower energy barrier for water vapor nucleation than neutral particles. In this way, as charged CCN could grow more rapidly than uncharged particles, their number would increase at a rate higher than that at which they are scavenged from the atmosphere by rainfall and other mechanisms. Condensable vapors (sulphuric and sulphurous acid) are known to play a major role as mediators of CCN formation too (Harrison, 2005), and therefore their presence in the atmosphere is essential for the cosmic ray effect.

The ion-aerosol near-cloud mechanism stems from the idea that cosmic ray intensity modulates the magnitude of aerosol charges within the cloud boundaries. These charged aerosols could migrate within the cloud and trigger the formation of new water droplets and ice particles or be captured by pre-existing water droplets. Yu (2002), tried to explain the influence of height upon the correlation between cosmic ray intensity and cloudiness (GCR–CN–CCN–Cloud Hypothesis), which is strong and positive in the low troposphere, based on the fact that the CN production rate depends on the ionization rate and also on the concentration of pollutants, namely sulphuric and sulphurous vapors, whose concentration is a maximum in the low troposphere.

Numerical simulations of new aerosol production have suggested that production is sensitive to changes in ionization from GCR in the lower troposphere (e.g. Yu and Turco, 2000), however, currently it is uncertain whether variability in atmospheric ionization due to the GCR flux could have a significant effect on either aerosol production or droplet growth (Marsh and Svensmark, 2003; Kazil and Lovejoy, 2004).

Ion mobility may also be lowered through attachment to solid particles, namely those that result from volcanic eruptions that are released in large amounts into the atmosphere. These eruptions also enhance the $SO_2$ aerosol concentration in the atmosphere, therefore contributing to CN formation as discussed before. The aerosol optical thickness of the atmosphere is an indirect measure of the concentration of these aerosols. Stothers (1996) noticed that, in the period 1881–1992, about 80% of $SO_2$ stratospheric aerosols were originated by volcanic eruptions.

Because the air electric conductivity is proportional to the product of ion density and ion mobility (see Eq. (2)) one should expect that cosmic radiation flux, artificial radioactivity and aerosol optical thickness of the atmosphere (see for instance Harrison, 2005) are somehow related to fair-weather electric field intensity (see Eq. (1)). In this work, we investigate to what extent the fair-weather electric field anomaly is correlated to these parameters.

## 2. Fair-weather electric field in Lisbon in the period 1955–1991

Hourly values of the atmospheric electric field intensity at ground level recorded at the meteorological station of Lisbon–Portela (38°47′N, 9°08′W) were used in the curve of the annual averaged values of the fair-weather electric field in Lisbon in the period 1955–1991, which is shown in Fig. 1a. All the values were recorded with a Benndorff electrograph with a probe at 1 m height. The data series was interrupted in 1975–1977 at which time the electrometer was switched off for maintenance reasons. The records restarted in March 1977. The same calibration procedure was used throughout all the operation periods. According to the international standards (Voeikov, 1965), fair-weather days were selected as those with cloudiness less than 0.2, wind speed less than 20 km $h^{-1}$ and with the absence either of fog or precipitation.

As the main feature of the curve represented in Fig. 1a, we see that the electric field strength shows a marked decline from 1955 through 1967. This trend was observed in almost all European stations and was pointed out by several authors (e.g. Hamilton, 1967; Pierce, 1972; Stewart, 1986; Harrison, 2002, Harrison and Carslaw, 2003). Pierce (1972) pointed out that proportionality existed between electric field anomalies and the frequency and magnitude of nuclear blasts in the atmosphere during this period. These tests ended by the end of 1962 and the electric field has gradually recovered to normal values during the next 5 years. Air ionization increased in that period due to the radioactive elements released to the atmosphere; therefore air conductivity also increased leading to the low values of the electric field strength recorded in that period. Increase in artificial radioactivity levels was also observed in Portugal (Fig. 1b). Lopes et al. (1975) measured the concentration of the $^{14}C$ radioactive isotope in the period 1950–1974 in Portuguese wines from the Douro region, and observed that the increase in concentration in the period 1954–1963 followed closely the frequency and magnitude of nuclear tests. From 1963 onwards, artificial radioactivity levels dropped gradually to normal values and therefore other factors should be considered to explain the fluctuations in the annual values of the electric field strength. Among these factors, cosmic radiation and volcanic aerosols certainly play a major role. We observe from Fig. 1a and c that, in general, the electric field varied inversely with cosmic radiation flux as should be expected from the relation between cosmic radiation and

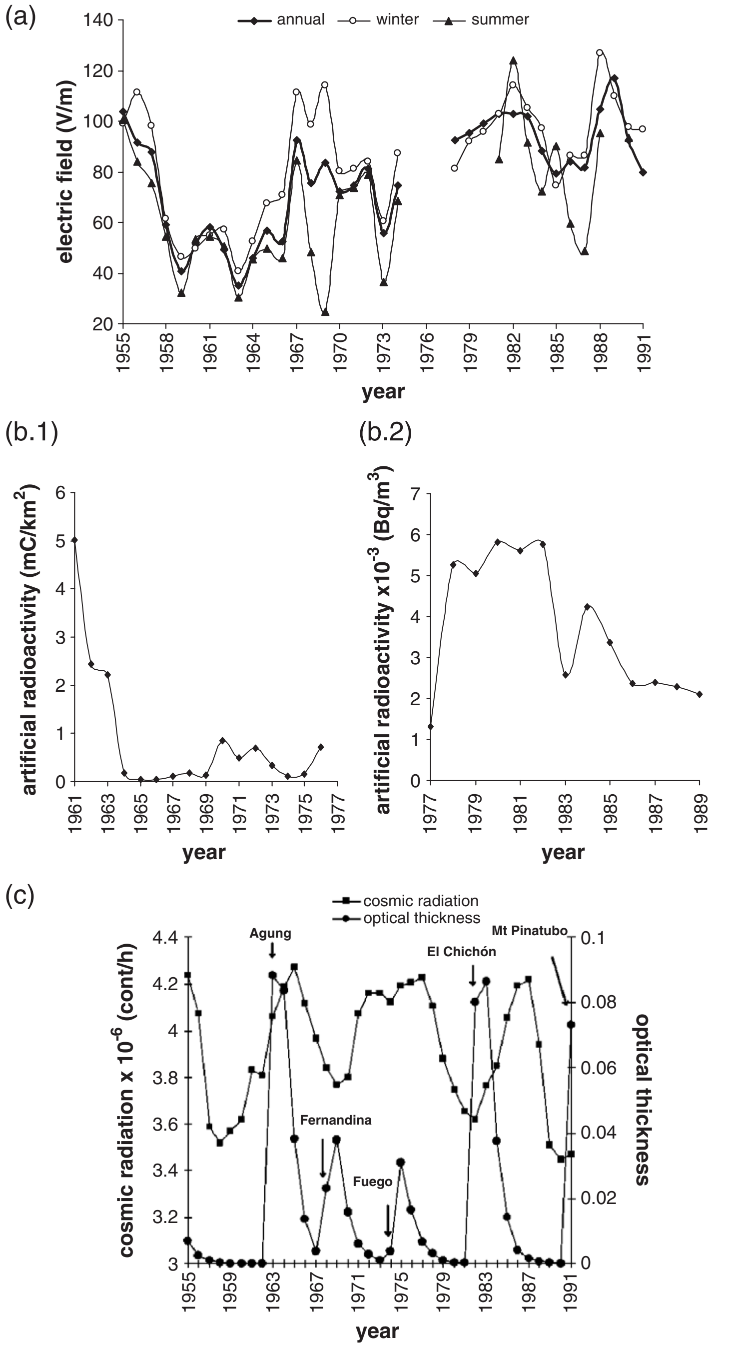


Fig. 1. (a) Annual averages of fair weather electric field strength in Lisbon in the period 1955–1991; (b) annual averages of artificial radioactivity flux in Lisbon, in the periods 1967–1976 (mC km$^{-2}$) and 1977–1991 (Bq m$^{-3}$); (c) variation of cosmic radiation and aerosol optical thickness between 1955 and 1991.

atmospheric ionization degree. In addition to short period fluctuations, it seems that cosmic radiation also displays long period fluctuations that might be responsible for a planetary reduction in the electric field strength during the twentieth century (Märcz and Harrison, 2003).

The contribution of volcanic aerosols, whose concentration may be inferred from measurements of aerosol optical thickness, to the increase in the electric field strength may have been significant in the years 1963–1965, the period in which the Agung eruption occurred, and may also explain the abrupt rise observed in the electric field in 1983 that corresponds to the big eruption of the volcano El Chichón (see Fig. 1a and c for both cases).

The average strength of the atmospheric electric field in the period 1978–1991, 93.1 V $m^{-1}$, was higher than that of the period 1967–1974, which was 79.6 V $m^{-1}$. As the Lisbon station is close to the international airport, some contribution to this augmentation might arise from the pollution due to increase in air traffic, even so this might not be the main reason because the same trend was recorded in Kew and Eskdalemuir (Märcz and Harrison, 2003).

The monthly averaged values of the fair-weather electric field in Lisbon in the period 1955–1991 are shown in Fig. 2. The upper values occur in wintertime while the lower ones occur in the early summertime. In fair-weather wintertime conditions, temperature inversions that keep pollutants close to the ground are quite frequent in Lisbon and therefore might contribute to an increase in the electric field. During summertime, the development of large boundary convective layers that enhance the fair-weather convective electric current may be responsible for the reduction of the fair-weather electric field strength. The seasonal variation of the fair-weather electric field strength in Lisbon shows the same trend previously observed in various stations in the northern hemisphere (e.g. Adlerman and Williams, 1996). Harrison (2002) and Märcz and Harrison (2003) observed the same trend with respect to the stations of Nagycenk (Hungary) and Eskdalemuir (Scotland). Adlerman and Williams (1996) pointed out that the seasonal variation in the concentration of Aitken nuclei may cause the seasonal behavior of the fair-weather electric field. The seasonal variation of the Aitken nuclei concentrations observed in Lisbon in the years 1961–1963 and 1968–1969 is shown in Fig. 3 and displays a trend similar to that of the electric field (see Fig. 2). For the case of Lisbon, this fact seems to corroborate the Adlerman and

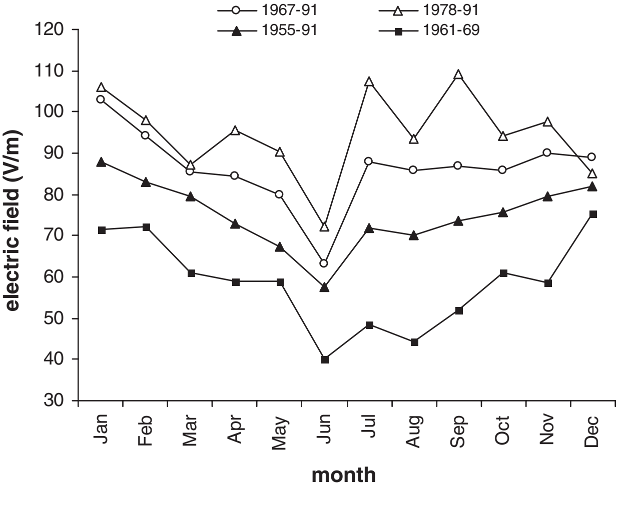


Fig. 2. Monthly averages of fair weather electric field strength in Lisbon between 1955 and 1991. Data of the years 1961–1963, 1968 and 1969 were used in the curve correspondent to the period 1961–1969.

Williams (1996) idea, though the few data available of Aitken nuclei concentrations do not allow a statistical significance to the trend to be assigned.

## 3. Correlations of cosmic radiation, artificial radioactivity and aerosol optical thickness relative anomalies with fair-weather electric field relative anomaly

In this study, we used relative anomalies rather than absolute values in order to identify and evince the respective relative variation trends. The electric field relative anomaly is defined as $((E-\bar{E})/\bar{E})$ where $E$ stands for the annual mean of the fair-weather electric field and $\bar{E}$ is the average value of the annual means in the period under consideration. Anomalies of the cosmic radiation flux, artificial radioactivity level and optical thickness are defined analogously.

In order to investigate if these relative anomalies are related to the electric field anomaly we note that they influence ion concentration and mobility in one way or another. Cosmic radiation and artificial radioactivity both influence ion concentration while aerosol concentration, which is considered here to be indirectly measured through the aerosol optical thickness, acts upon ion mobility mainly. Due to the few data available, the possible influence of the Aitken nuclei upon the fair-weather electric field is not studied separately, although its concentration is assumed to contribute to aerosol optical thickness.

Therefore, by assuming that air conductivity, $\sigma$, is some unknown function of cosmic radiation flux, $C_R$, artificial radioactivity intensity, $R_a$, and aerosol optical thickness, $\tau$, Eq. (1) reads:

$$J_z = (\sigma_0 + f(C_R;\ R_a;\tau))E_z \tag{3}$$

where $\sigma_0$ is air conductivity without the influences of cosmic radiation, artificial radioactivity and for null aerosol optical thickness.

Records of artificial radioactivity levels exist for Lisbon together with data of cosmic radiation flux for approximately the same geomagnetic latitude but, unfortunately, no records were found for the fair-weather current $J$ in Lisbon. Therefore, we used the principal components analysis (PCA) technique in order to investigate if the anomalies of cosmic radiation

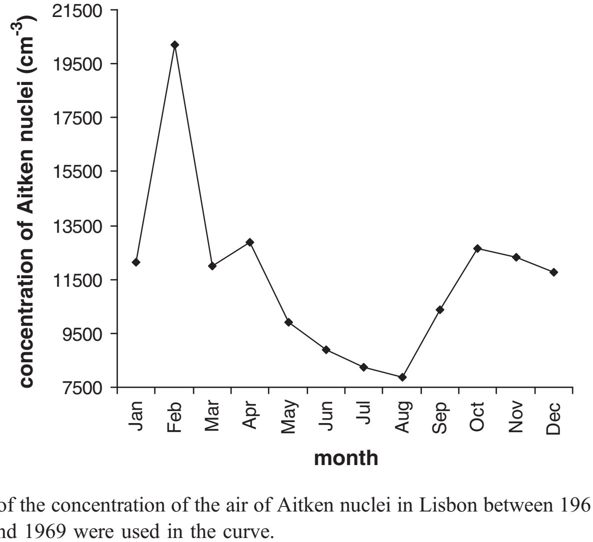


Fig. 3. Monthly averages of the concentration of the air of Aitken nuclei in Lisbon between 1961 and 1969. Data for the years 1961–1963, 1968 and 1969 were used in the curve.

flux, artificial radioactivity intensity, and aerosol optical thickness really affect the electric field strength in Lisbon and see which of these influences is of major significance. The PCA technique is widely used to diagnose the temporal patterns of atmospheric attributes, intending to facilitate the understanding of the underlying temporal data structure.

This multivariate method was applied to the data set in order to evaluate the relationship between the electric field strength, cosmic radiation flux, artificial radioactivity intensity, and aerosol optical thickness. The procedure adopted in this work consists of grouping the principal components parameters that display the same temporal variability, with the purpose of looking for "causality relationships". The results are shown in Figs. 4 and 5.

In Fig. 4 we may see that the first component that explains 52.8% of the residual variance in the data is a linear combination of the relative anomalies of the artificial radioactivity, aerosol optical thickness and cosmic radiation flux and is statistically significant ($r=0.464$ and $p$-value$=0.039$, see Appendix). The physics of the problem as described by Eq. (3) means that some relationship is assumed among these variables, the electric field strength and the fair-weather electric current. Both components are candidates to represent the electric field strength relative anomaly because this is expected to vary directly with the relative anomalies of the optical thickness and inversely with those of cosmic radiation flux and artificial radioactivity. This hypothesis was not entirely verified with the first component with respect to artificial radioactivity. Subsequent analysis showed that the relative anomalies of the artificial radioactivity level and the electric field strength are not statistically correlated (see Table 1). On the other hand, as shown in Fig. 5, the trends of the first component and the anomaly of the electric field strength are quite similar.

Yet, none of these components seems to fit the physics of the fair-weather current in relation with optical thickness, cosmic radiation flux and artificial radioactivity intensity. This is consistent with the hypothesis that one of the principal components does represent the electric field anomaly, which is an expected result because the principal components are orthogonal and in view of Eq. (3) the fair-weather electric current is not orthogonal to the electric field strength and therefore should not appear as one of the components in Fig. 4.

The previous analysis substantiates the hypothesis that the relationship advanced in Eq. (3) exists for the data recorded at the Lisbon station. Therefore, in what follows we investigate

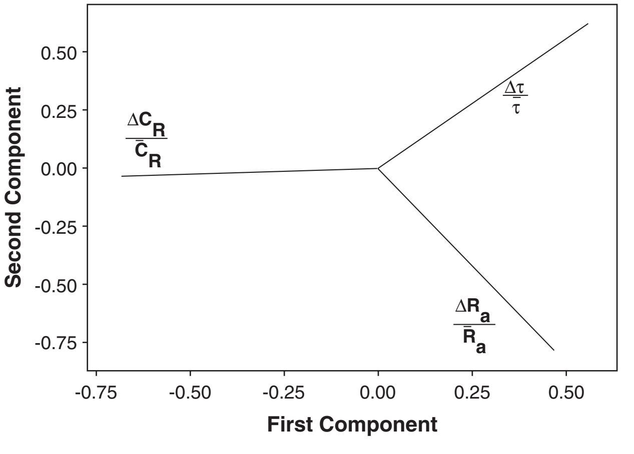


Fig. 4. Analysis of the main components of relative anomalies of aerosol optical thickness, of the cosmic radiation and artificial radioactivity intensity in Lisbon, in the period 1967–1991.

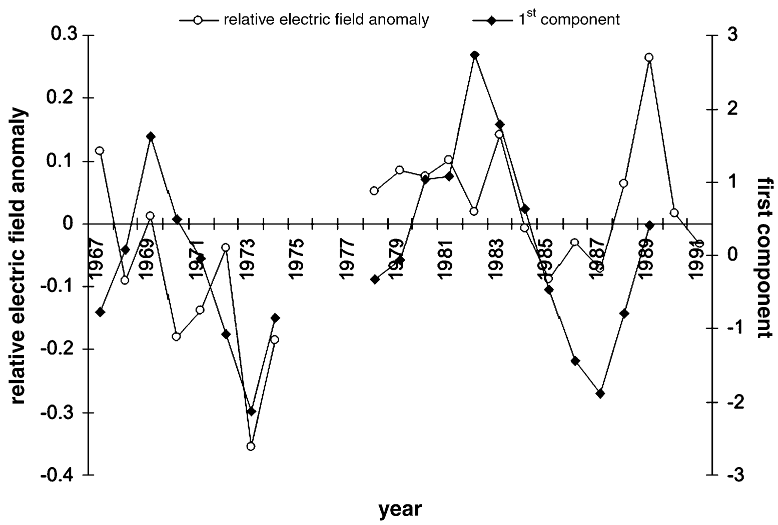


Fig. 5. Annual variation of the first component and of the electric field relative anomaly in Lisbon, in the period 1967–1991.

possible correlations between the relative anomalies of fair-weather electric field strength and those of cosmic radiation, aerosol optical thickness and artificial radioactivity.

### 3.1. Influence of cosmic radiation

It is widely recognized that galactic cosmic rays are the main source of ionization in the troposphere therefore influencing the electric conductivity (e. g. Tinsley, 2005). In order to verify if correlations suggested by Eq. (3) do really exist for the data recorded at the station of Lisbon–Portela in the period 1967–1991, linear regression analysis was carried out while the results were checked through the Pearson test. The reason for not having considered the years 1955–1966 in the regression analysis is that the huge value of artificial radioactivity intensity completely masks other influences upon the fair-weather electric field. In the years 1961–1976, the artificial radioactivity intensity was measured at Lisbon–Portela through the concentration of radioactive particles deposited on a horizontal sheet (Fig. 1b.1) having been replaced by the volumetric method since 1977 (Fig. 1b.2). The year of 1977 was also excluded from the analysis due to the absence of data in the few first months of that particular year.

Data series of cosmic radiation flux in Lisbon are not available for the years 1955–1991. Although cosmic radiation flux changes with latitude, it does not practically change with

Table 1
Correlation coefficients ($r$) of the atmospheric electric field anomaly with cosmic radiation ($\Delta C_R/\bar{C}_R$), aerosol optical thickness ($\Delta\tau/\bar{\tau}$), and artificial radioactivity ($\Delta R_a/\bar{R}_a$) anomalies in various periods

| Time series (sample size) | $\Delta C_R/\bar{C}_R$ | $\Delta\tau/\bar{\tau}$ | $\Delta R_a/\bar{R}_a$ |
|---|---|---|---|
| | $r$ ($p$-value) ($\gamma$) | $r$ ($p$-value) | $r$ ($p$-value) |
| 1967–1991 (22) | −0.529 (0.011) (0.70) | 0.159 (0.481) | 0.185 (0.435) |
| 1967–1991[a] (14) | −0.637 (0.014) (0.65) | −0.334 (0.243) | 0.178 (0.560) |

The respective $p$-value is also shown as well as the probability of detecting a true effect ($\gamma$).
[a] The values corresponding to the years that present high aerosol optical thickness have been removed.

longitude. Therefore, we used a data series of the surface neutron counter recorded at the station of Climax–Colorado (39°37′N, 106°18′W) which is located at a geomagnetic latitude (GL) of 47°N (Ziegler, 1998) relatively close to that of the Lisbon–Portela station (38°47′N, 9°08′W, GL 40°N). The results are summarized in Table 1.

It was found that the cosmic radiation flux relative anomaly is negatively correlated with the fair-weather electric field relative anomaly and is statistically significant in the years 1967–1991 (see Fig. 6a and Table 1). As a general criterion, statistical significance was considered whenever the $p$-value stayed below 0.05. At first sight, this result matches the physics of the interaction of cosmic radiation with atmospheric gases for the reason that the increase in cosmic radiation flux produces higher degree of ionization and therefore lessens the electric field.

However, when we investigated seasonal correlations we found a marked difference between winter and summer (Table 2). In fact, the negative correlation between the relative anomalies of cosmic radiation flux and fair-weather electric field is relatively high in wintertime (Fig. 6b–c), is weak in summertime (Fig. 6d–e) while during autumn and spring it stays close to the annual averaged values. This result indicates that the inverse correlation between the relative anomalies of fair-weather electric field and cosmic radiation flux would not be as simple as the basic mechanism of direct air ionization by cosmic rays suggests, and that other mechanisms might be active. In order to find a reliable explanation for this seasonal effect we considered the GCR–CN–CCN–Cloud Hypothesis that was referred before.

Actually, the mediation of droplet formation by the $SO_2$ aerosol would be effective preferentially in wintertime when relative humidity is high. In this way, the effect of cosmic radiation would be more pronounced in wintertime, leading to increase in cloud cover and negative charge accumulation in low level clouds, therefore contributing to fair-weather electric field reduction at the ground level. Due to the low level of relative humidity in summertime this mechanism would not be as effective as it would be in wintertime, therefore explaining the reduction in the correlation observed in summertime. However there is no clear evidence that this mechanism is important because while Pallé et al. (2004) found a correlation of 95–100% between atmospheric ionization and low cloud cover over Portugal, Kazil and Lovejoy (2004) pointed out that the nucleation rate close to the surface due to cosmic radiation is very weak.

Another important aspect that might contribute to the higher correlation between cosmic rays and fair-weather electric field comes from the fact that in wintertime the boundary layer convection is strongly reduced with respect to summertime. As a result, the wintertime electric current is nearly ohmic, and consequently fits the assumptions behind Eq. (3) more closely, then the influence of global effects will be more clearly seen in the electric field. This idea finds support from the fact that the correlation coefficient between the electric field observed in Lisbon in Winter and the Carnegie curve is 64.7% ($p$-value = 0.001). This same tendency has been noticed by other authors (e. g. Israelsson and Tammet, 2001).

### *3.2. Influence of aerosol optical thickness*

As said before we assumed that the aerosol optical thickness is an indirect global measure of the concentration of aerosols in the atmosphere. These include those of planetary origin like the volcanic aerosols and local ones such as the Aitken nuclei.

No data series of aerosol optical thickness in Lisbon are available for the period 1967–1991. Instead we used those of the station NOAA–NGDC–Paleo (39.29°N) that is located at almost at the same latitude as Lisbon. As observed in Table 1, the correlation between the relative anomaly of aerosol optical thickness, which is a measure of aerosol concentration in the atmosphere, and

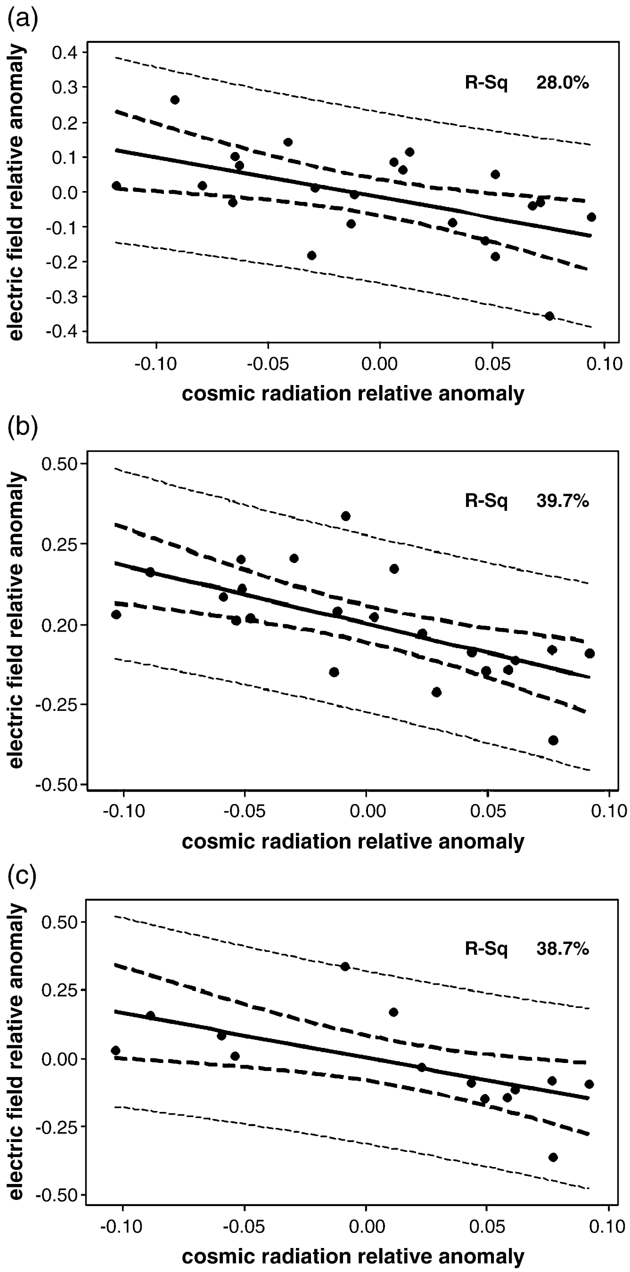


Fig. 6. Relative anomaly of the fair weather electric field as correlated with cosmic radiation, in Lisbon, in the period 1967–1991: (a) annual means; (b) wintertime; (c) wintertime (excluding the years with high aerosol optical thickness); (d) summertime; (e) summertime (excluding the years with high aerosol optical thickness). Dotted line–prediction bands; dashed line–trust interval; continuous line–regression; $R$-Sq–square of correlation coefficient.

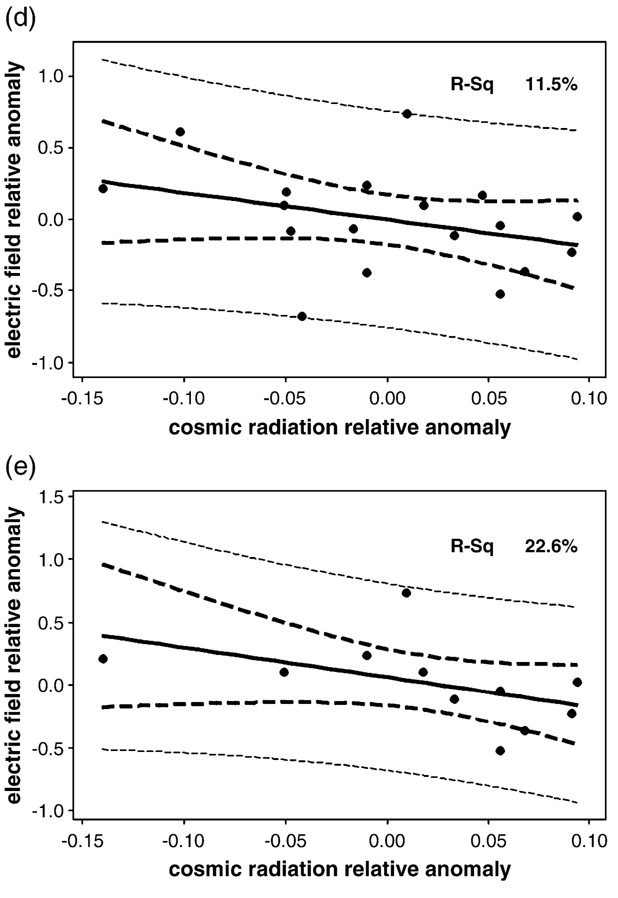


Fig. 6 *(continued).*

the artificial radioactivity relative anomaly is poor. The big eruption of the volcano El Chichón (Mexico) that occurred in 1981 originated a strong increase in the aerosol optical thickness of planetary extent in the period 1982–1984 (Fig. 1c). In this period, the correlation is positive, as should be expected from the fact that the aerosols bind small ions, therefore decreasing the air conductivity and leading to increase of the electric field. The weakness of the correlation is consistent with the idea that volcanic aerosols mainly influence the stratospheric electric field (Tinsley, 2005), and indicates that except for the years in which the aerosol optical thickness is high, the fair-weather electric should be mostly influenced by cosmic radiation.

### *3.3. Influence of artificial radioactivity intensity*

Natural and artificial radioactivity both contribute to ionization in the low levels of the atmosphere. As Lisbon is located close to the sea and because natural radioactivity is not present over the oceans, variations are to be expected with changes in wind direction. However, the wind

Table 2
Correlation coefficients ($r$) of the atmospheric electric field anomaly with the seasonal anomalies of cosmic radiation in various periods

| Time series (sample size) | Autumn<br>$r$ (p-value) ($\gamma$) | Winter<br>$r$ ($p$-value) ($\gamma$) | Spring<br>$r$ ($p$-value) | Summer<br>$r$ ($p$-value) |
|---|---|---|---|---|
| 1967–1991 (22) | −0.487 (0.025) (0.60) | −0.670 (0.002) (0.93) | −0.069 (0.762) | −0.339 (0.169) |
| 1967–1991[a] (14) | −0.708 (0.005) (0.80) | −0.622 (0.018) (0.65) | −0.482 (0.081) | −0.476 (0.139) |

The respective $p$-value is also shown as well as the probability of detecting a true effect ($\gamma$).
[a] The values corresponding to the years that present high aerosol optical thickness have been removed.

patterns in Lisbon are quite stable over the year and this is reflected in the natural radioactivity levels that are also quite stable over the year and over all the period under study. Therefore, only artificial radioactivity was considered due to the large variation that it presented in the period under study.

We used data series of artificial radioactivity concentration recorded at the station of Lisbon–Portela in the periods 1967–1976 (mC km$^{-2}$) and 1977–1991 (Bq m$^{-3}$). As shown in Fig. 2b, the units in which the artificial radioactivity level is expressed are different in each of these two periods. However, the units are irrelevant to the effect of our study because we used relative anomalies $(R_a - \bar{R}_a)/\bar{R}_a$ that are non-dimensional and in which the deviations of mean values were set to scale.

As shown in Table 1, the relative anomaly of the fair-weather electric field is practically uncorrelated with the artificial radioactivity concentration relative anomaly (note also the respective very high $p$-values in Table 1). In fact during this period, the artificial radioactivity concentration is very low as compared with that recorded in the years 1961–1966. High correlation between electric field and artificial radioactivity concentration should be expected to occur in this period. However, the data series refer to concentration of deposited radioactive particles on a horizontal sheet that is not entirely proportional to radioactive aerosol concentration in the atmosphere due to the fact that the concentration of deposited particles itself varies with the electric field strength.

## 4. Conclusions

The curve of the annual averages of the fair-weather atmospheric electric field in Lisbon shows that a strong reduction occurred in the period 1957–1967. This same tendency was observed by other authors that studied the behaviour of the fair-weather electric field recorded in the same period in some stations of the northern hemisphere, namely in the stations at Kew (England) and Eskdalemuir (Scotland). The reduction in the fair-weather electric field strength was endorsed by the increase in the artificial radioactivity concentration in the atmosphere due to nuclear tests realized in that period.

It was found that the relative anomalies of fair-weather electric field and cosmic radiation flux were negatively correlated and that this correlation was statistically significant under Pearson's test. The analysis of the seasonal behaviour of this correlation indicated that it is strong in wintertime and mild in summertime while it follows the annual mean in autumn and in spring. A possible explanation for the seasonal effect might be that cosmic rays, instead of acting directly through air ionization, would act indirectly by enhancing droplet and cloud formation followed by ion capture and formation of a negative layer in the lower atmosphere, which would reduce the electric field strength. This mechanism that matches the GCR–CN–CCN–Cloud Hypothesis

(Yu, 2002) might be active and seems corroborated by the work of Pallé et al. (2004). Nevertheless, the work by Kazil and Lovejoy (2004) weakens this hypothesis by pointing out that the rate of formation of CN by cosmic radiation is very weak. Another explanation might be found in the fact that the boundary layer convection is strongly suppressed in wintertime with reduction of the convection electric current. In this case, as the fair-weather electric current is practically ohmic, the influence of cosmic radiation would appear more clearly.

The relative anomaly of the fair-weather electric field was found not to be significantly correlated either with the relative anomaly of aerosol optical thickness or with the relative anomaly of artificial radioactivity intensity.

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## Appendix A. The sample size in Pearson's correlation

The statistical correlation can be misleading, and therefore one has to remember to think beyond the numerical association between two variables, and not to infer causality too easily (Stuart and Ord, 1994; Draper and Smith, 1998). A key thing to remember when working with correlations is never to assume that a correlation means that a change in one variable causes a change in another. The *p*-value indicates the probability that the result obtained in a statistical test is due to chance rather than a true relationship between measures. Small *p*-values indicate that it is very unlikely that the results were due to chance. Therefore, if the *p*-value is small, statisticians would be confident that the result obtained is "real". By means of the *p*-value, one obtains the significance level for a statistical test. The *p*-value represents the likelihood, under the assumption that the null hypothesis is true, that the data would yield the obtained results. The statistical significance is the degree to which a value is greater or smaller than would be expected by chance. Typically, a relationship is considered statistically significant when the probability of obtaining that result by chance is less than if there were, in fact, no relationship in the population. Correlation criteria seek to analyze the similarity and differences between two sets of data. We have looked at Pearson's test as a useful descriptor of the degree of linear association between two variables. But how do we know when a correlation is sufficiently different from zero to assert that a real relationship exists? What we need is some estimate of how such variation in r can be expected just by random chance. In fact, what we need is to be able to draw a line, which tells us that above that line a correlation will be considered as a real correlation and below that line the correlation will be considered as probably due to chance alone (Fig. 6). It is well known that for small sample size, the correlation can vary markedly even when the null hypothesis is true (i.e., if chance is a reasonable explanation for the correlation).

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