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The Conductivity of the Air and Other Electrical Parameters in Relation to Meteorological Elements and Air Pollution in Athens

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With 3 Figures

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Summary

The annual and diurnal variation of the conductivity near the ground at Athens, based on long-term data, are presented. The diurnal double oscillation is a characteristic of the "atmospheric electric climate" of Athens. In addition, the influence of air pollution due to smoke and sulfur dioxide and of wind speed (as an element affecting the dispersion of pollutants) on large ion concentration and on conductivity has been examined. The air pollution, which is often severe in Athens area, results in decreasing conductivity and increasing large ion concentration, while the influence of wind speed is also pronounced. The results justify the use of conductivity as a pollution index. Finally the plausible influence of air temperature and relative humidity and of their rate of change on air electrical conductivity, has been examined. The results are ambiguous and depending on the season, especially for relative humidity.

1. Introduction

The electrical conductivity of the air is mainly due to the presence of highly mobile (small) ions produced in the atmosphere by cosmic rays and local radioactive sources. A balance is maintained since the small ions are being removed from the atmosphere at the same rate that they are being produced. They are removed by recombination with oppositely charged small ions and by attachment to larger aerosol particles. These recombination and attachment processes thus determine the life times of small ions in the atmosphere and secondarily of the conductivity, since its value is formed predominantly by the small ion concentration in the air. Ion lifetimes near the earth's surface vary from 20 sec in highly polluted air to 300 sec in very clean air (Cobb, 1973 a).

The conductivity of the air, being largely controlled by aerosol conditions, the natural radioactivity in the boundary layer and other meteorological elements, is preferable to the other atmospheric electric parameters for comparisons to the meteorological parameters (Dolezalek, 1969).

In Greece, an atmospheric electrical station has been installed in 1968 and measurements have been regularly made ever since. The diurnal and annual variations of air conductivity near the ground have been examined by Retalis and Zervos (1976). The influence of particulate air pollution (smoke) and the indirect influence of gaseous air pollution (sulfur dioxide) and wind speed on air electrical parameters has been examined by Retalis and Carapiperis (1972), Retalis (1977) and Zambakas et al. (1985). In addition, the importance of electrical parameters, especially small ions concentration or conductivity, as a sensitive tool for monitoring radioactive fallout has been demonstrated by Retalis (1987) and Retalis and Pitta (1989).

This report presents new long-term conductivity data (1968–1980) and discusses the influence of particulate air pollution due to smoke and of wind speed on electrical conductivity and large ions concentration. In addition, the possible influence of gaseous air pollution due to sulfur dioxide on the above air electrical parameters is discussed (SO_2 does not directly influence the conductivity, however it may indicate particulate air pollution). In addition, the possible influence of ambient air temperature and relative humidity on conductivity is examined.

2. Instruments and Data Used

The atmospheric electric station of the National Observatory of Athens (NOA) is installed at the top of the Nymphs hill (107 m above mean sea level) situated in the centre of Athens, facing the Acropolis. The top of the hill is relatively flat, the hill is not steep while the altitude difference between the top of the hill and Athens centre is approximately 30 metres. The atmospheric electric instruments have been manufactured by the Laboratory of Physics in Aarau, Switzerland, by L. Saxer and W. Sigrist.

The conductivity of the air near the ground is measured by a Gerdien conductivity meter consisting of two conducting capacitor electrodes arranged so that the air sample is constrained to flow between them. The accelerating voltage V is applied to the outer tube, while the inner tube is connected to the ground through a high and precise resistance R. Technical characteristics are as follows:

Central probe length = 0.40 m
Radius of the central probe = 0.0115 m
Radius of the outer tube = 0.035 m
Accelerating voltage V applied between the electrodes = 17.7 V
Capacitance C of the instrument = 20 pF

The air stream is made so rapid and the field in the interior of the tube so weak that only a small fraction of the available ions is collected. In this case the instrument exhibits a linear relationship between applied accelerating voltage and collected ion current. The operating critical mobility should be at least a factor of 3 higher than ion counting critical mobility, to ensure that the instrument operates in "the conductivity range" and that the ion counting region will not be reached (Anderson and Bailey, 1991). In our case the minimum air stream velocity is 2.4 m/sec which, assuming uniform velocity distribution, corresponds to a minimum flow rate $\Phi = 9.2 \times 10^{-3}\,\mathrm{m^3/sec}$. Using the equation $k_c = \varepsilon_0 \cdot \Phi / C \cdot V$, where ε_0 = dielectric constant (C and V have been given above), we obtain an ion counting critical mobility $k_c = 2.3 \times 10^{-4}\,\mathrm{m^2}/V \cdot \mathrm{sec}$. Since the operating air stream velocity is 10 m/sec (Saxer and Sigrist, 1966), 4 times greater than the minimum, the critical mobility is also well above the ion counting critical mobility, thus ensuring that the instrument is operating in the conductivity range and the data are valid.

Large ions are those with mobility greater than $2.5 \times 10^{-8}\,\mathrm{m^2}/V \cdot \mathrm{sec}$. The ambient potential is 308 V/m for all weather and 298.5 V/m for fair weather. The negligible difference between those figures is a consequence of the very low thunderstorm activity over Athens area: The mean annual number of thunderstorm days for 80 years is 18 (Michalopoulou, 1978), a number confirmed by the data of NOA climatic station (in operation since 1894). A thunderstorm day is defined as a day during which thunder is heard at the station, according to the AMS glossary.

In addition we note that the value of the Ω parameter varies from 1.1 in May to 2.1 in December, while its mean annual value is 1.4 (Retalis, 1991). These values of Ω prove that Ohm's low is fulfilled in a satisfactory way at NOA station.

The instruments for the measurement of smoke and sulfur dioxide have been manufactured by Glass Developments Ltd., London. Smoke is measured by aspirating air through a filter paper and estimating the darkness of the stain with a reflectometer. Sulfur dioxide is measured by bubbling air through a dilute H_2O_2 solution in a Drechsel bottle and titrating.

The hourly values of the atmospheric electric parameters (conductivity, small and large ions concentrations) have been obtained from the Bulletin of Atmospheric Electricity (1968–1980), published by the NOA. Daily values of sulfur dioxide and smoke have been obtained from the Bulletin of Air Pollution (1977–1978) and hourly values of meteorological parameters (temperature, relative humidity and wind speed) from the Climatological Bulletin (1968–1980).

3. Diurnal and Annual Variation of the Air Electrical Conductivity

The diurnal variation of the conductivity at a specific station clearly depicts its "atmospheric electric climate", on the condition that the annual amplitude would be small. In Figures 1 and 2 the average diurnal and annual course of atmospheric conductivity are given, based on mean hourly values for all days of the year and for 13 years (1968–1980). The scope is to compare the results of these long-term data with the results of a previous report (Retalis and Zervos, 1976) based on 5 years data, thus leading to more reliable conclusions about the "atmospheric electric climate" of Athens.

The diurnal variation of the air positive and negative conductivity, presents a double oscillation for all months and for the year. The hours of maxima and minima, the amplitude and the overall configuration of the diurnal and annual course is similar to the results of the former 5 years investigation (Retalis and Zervos, 1976), where detailed explanations have been given.

Bearing in mind that the variations of atmospheric conductivity is almost exclusively due to the changes in small ion concentration, according to the relation:

$$\Lambda = \lambda_+ + \lambda_- = e\sum_i n_+ K_+ + e\sum_i n_- K_-$$

(Chalmers, 1967; Israel, 1971)

where λ is the conductivity, n is the small ion concentration and K their mobility.

In conclusion we may note the following:

(a) The analytical diagrams of diurnal variation for each month separately which are not presented here in order to economize space, reveal that the morning maximum is the main one during the winter months, while the opposite is observed during the summer months owing to the stronger convective activity.

(b) The early morning conductivity minimum occurs a little after sunrise, between 7–9 h, according to the month. The minimum, for each month, coincide with the observed corresponding maximum in the electric field strength. This minimum may be attributed to the low concentration of small ions, owing to their destruction by recombination with large ions and neutral nuclei. These nuclei increase in number because they are produced by different polluting sources (industries, vehicular traffic) while on the other hand they are subjected to limited diffusion since the convective activity has not yet developed. This minimum may also be associated with the electrode effect (Cobb, 1968).

(c) The night maximum (around 4 h) is higher (almost equivalent to the afternoon maximum, around 16 h).

(d) The highest values of the conductivity appear in summer, due to enhanced convection and lower pollution levels while annual variation is relatively small (Fig. 2).

(e) The ratio of the positive to the negative conductivity is 1.4, a figure which agrees fairly well with previous investigators (Law, 1963; Brownlee, 1975). This ratio depends on electrode effect but, under the given conditions explained in page four (station description), we believe that the electrode effect has been minimized.

(f) The mean annual values for the 13 year period were estimated:

$$\lambda_+ = 313.4 \times 10^{-17} \Omega^{-1} m^{-1}$$
$$\lambda_- = 224.6 \times 10^{-17} \Omega^{-1} m^{-1}$$

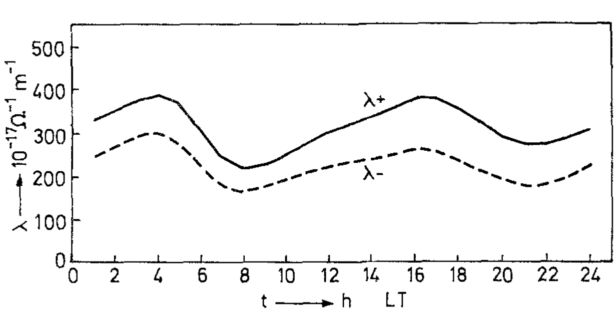

Fig. 1. Mean diurnal course of positive (———) and negative (– – –) atmospheric conductivity above Athens

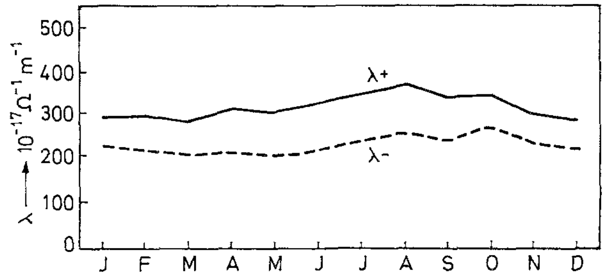

Fig. 2. Annual course of positive (———) and negative (– – –) atmospheric conductivity above Athens

while the corresponding 5 year values (Retalis and Zervors, 1976) were:

$\lambda_+ = 321.0 \times 10^{-17} \Omega^{-1} m^{-1}$

and

$\lambda_- = 258.0 \times 10^{-17} \Omega^{-1} m^{-1}$.

The observed small decrease in conductivity must be attributed to the increase of particulate air pollution in Athens area.

(g) The variation of the annual average of both polar conductivities over the years since 1968 is presented in Fig. 3. The regression lines are plotted while the regression equation are as follows:

$\lambda_+ = -1.66\,t + 323.18$ (t stands for time)

$\lambda_- = -6.23\,t + 268.34$

The regression lines reveal the existence of a trend, which is more pronounced for negative conductivity. In order to test the randomness against trend alternative, we proceeded to the Mann-Kendall rank statistic τ (WMO, 1966). We used the 13 mean yearly values of polar conductivities over the period 1968–1980 to compute the statistic $P = \sum_{i=1}^{N-1} n_i$, where $N = 13$. The statistic τ we require is derived from N and P by the relation $\tau = (4P/N(N-1)) - 1$. The value of τ can be used as the basis of a significance test by comparison with the values:

$(\tau_t) = 0 \pm 1.96\sqrt{(4N + 10)/9N(N-1)}$,

for a confidence level 95%.

For $N = 13$, $(\tau_t) = \pm 0.412$

For λ_+ we obtain $\tau = 0.231$ while for λ_- we obtain $\tau = 0.487$.

Since the value $\tau = 0.231$ lies inside the limits set by (τ_t), we conclude that no trend is apparent in positive conductivity. Since the value $\tau = 0.487$

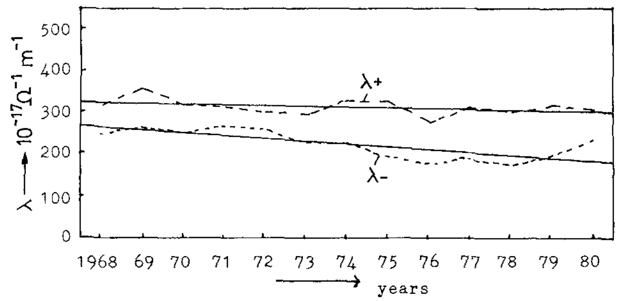

Fig. 3. Variation of the annual average of positive (— — —) and negative (· · · ·) atmospheric conductivity over the years 1968–1980. The regression lines $\lambda = f(t)$ are plotted (———)

Table 1. *Cold Months Correlation Coefficients (R) Between Conductivity* (positive λ_+ and negative λ_-) *and (1) Smoke (S), (2) Sulfur Dioxide (SO_2) and (3) Wind Speed (U).* $\triangle R$ = Correlation Coefficient error, P (‰) = Possibility for the correlation to be random

		O	N	D	J	F	M
λ_+, S	R	− 0.614	− 0.543	− 0.515	− 0.701	− 0.520	− 0.379
	$\triangle R$	0.080	0.097	0.128	0.065	0.099	0.109
	P	< 1	< 1	< 3	< 1	< 1	< 5
λ_-, S	R	− 0.285	− 0.567	− 0.667	− 0.594	− 0.502	− 0.445
	$\triangle R$	0.118	0.093	0.097	0.083	0.102	0.102
	P	< 5	< 1	< 1	< 1	< 1	< 1
λ_+, SO_2	R	− 0.528	− 0.561	− 0.340	− 0.576	− 0.522	− 0.415
	$\triangle R$	0.092	0.094	0.154	0.086	0.099	0.105
	P	< 1	< 1	< 5	< 1	< 1	< 1
λ_-, SO_2	R	− 0.225	− 0.604	− 0.559	− 0.481	− 0.530	− 0.514
	$\triangle R$	0.122	0.087	0.120	0.105	0.098	0.093
	P	< 80	< 1	< 1	< 1	< 1	< 1
λ_+, U	R	0.598	0.770	0.680	0.595	0.732	0.226
	$\triangle R$	0.082	0.056	0.094	0.083	0.063	0.121
	P	< 1	< 1	< 1	< 1	< 1	< 80
λ_-, U	R	0.422	0.807	0.784	0.781	0.819	0.350
	$\triangle R$	0.105	0.048	0.067	0.050	0.045	0.110
	P	< 1	< 1	< 1	< 1	< 1	< 8

lies outside the limits set by (τ_t), we conclude that a falling trend exists in negative conductivity.

The same results have been obtained using the mean monthly values of polar conductivities for 1968–1980 (156 values). For $N = 156$ we derive $(\tau_t) = \pm 0.1058$. For λ_+ we obtain $\tau = 0.072$ while for λ_- $\tau = 0.329$. It is obvious that a distinct trend is apparent only for negative conductivity.

The difference observed in Fig. 3 between the two polar conductivities must be attributed to the different behaviour of negative small ions owing to their increased mobility, compared to the mobility of the positive small ions.

(h) In general the observed conductivity of the NOA station is small in comparison to the results of other investigators (Gish, 1951), a fact attributed to the urbanization and severe pollution of Athens area.

4. Influence of Air Pollution and Wind Speed on Electrical Parameters

The use of the air conductivity as a pollution index, which was suggested by Cobb and Wells (1970) seems justifiable both because of the considerable number of successful demonstrations which have occurred (Misaki and Takeuti, 1970; Morita, 1971; Misaki et al., 1972) and because a measurement of conductivity inherently provides a useful integration over a great volume of sample and the entire ion spectrum (Cobb, 1973 b; Anderson, 1974).

Tables 1 and 2 demonstrate the results of the attempted correlation between conductivity or large ion concentration of both signs and pollution factors; sulfur dioxide, smoke and wind speed (as a parameter affecting the dispersion of pollutants). The correlation coefficients are rather considerable and variable. As the air pollution by sulfur dioxide and smoke increases, the conductivity decreases while the large ion concentration increases. Gaseous air pollution due to sulfur dioxide may indicate particulate air pollution, thus affecting indirectly the air conductivity. The direct influence of particulate air pollution due to smoke may be explained as following:

In polluted urban areas, the recombination of small ions near the ground is negligible. Under equilibrium conditions and if the size distribution of aerosol particles does not change significantly

Table 2. *Cold Months Correlation Coefficients (R) Between Large Ions* (positive N_+ and negative N_-) *and (1) Smoke (S), (2) Sulfur Dioxide (SO_2) and (3) Wind Speed (U).* $\triangle R$ = Correlation Coefficient error, P(‰) = Possibility for the correlation to be random

		O	N	D	J	F	M
N_+, S	R	0.381	0.707	0.870	0.816	0.690	0.737
	$\triangle R$	0.126	0.076	0.042	0.050	0.076	0.060
	P	< 10	< 1	< 1	< 1	< 1	< 1
N_-, S	R	0.892	0.802	0.899	0.820	0.704	0.534
	$\triangle R$	0.027	0.049	0.027	0.042	0.069	0.091
	P	< 1	< 1	< 1	< 1	< 1	< 1
N_+, SO_2	R	0.245	0.721	0.653	0.304	0.705	0.666
	$\triangle R$	0.139	0.073	0.100	0.135	0.073	0.073
	P	< 100	< 1	< 1	< 47	< 1	< 1
N_-, SO_2	R	0.553	0.794	0.674	0.693	0.722	0.482
	$\triangle R$	0.093	0.050	0.078	0.067	0.065	0.098
	P	< 1	< 1	< 1	< 1	< 1	< 1
N_+, U	R	− 0.567	− 0.817	− 0.740	− 0.678	− 0.560	− 0.559
	$\triangle R$	0.100	0.051	0.079	0.081	0.100	0.090
	P	< 1	< 1	< 1	< 1	< 1	< 1
N_-, U	R	− 0.762	− 0.787	− 0.673	− 0.710	− 0.615	− 0.336
	$\triangle R$	0.056	0.052	0.078	0.063	0.085	0.114
	P	< 1	< 1	< 1	< 1	< 1	< 10

over time, the small ion concentration is linearly correlated to the density of aerosol particles (Israel, 1971) and hence to the degree of pollution. Ion depletion by attachment to aerosol particles leading to the reduction of conductivity is a process depending strongly on the size distribution of the aerosol particles. Over Athens area there are no heavy industry installations, heating is made exclusively by oil fuel and there is practically no area devoted to agricultural practices. The percentage contribution of each polluting source in smoke and sulfur dioxide over Athens area is as follows (P.E.P.C., 1989):

	Vehicles	Heating	Industry
Smoke	64	17	19
Sulf. dioxide	7	21	72

It is evident that smoke is mainly emitted by vehicles while sulfur dioxide is mainly emitted by industrial installations.

From the above we can deduce that the increased particulate air pollution leads to the decrease of small ion concentration, owing to their becoming, by attachment, large ions (Retalis, 1977). This influence also explains the fact that the large ion concentration at the NOA is much larger than the corresponding small ion concentration (Retalis, 1983). This is a characteristic feature of a heavily polluted area, as is the centre of Athens.

From Tables 1 and 2 it is obvious that when the wind speed increases, positive and negative conductivity increases while the large ion concentration decreases. This is explained as following: The increase in wind speed results in higher dispersion and decrease of large ions and condensation nuclei as opposed to small ions, which are subjected to smaller destruction owing to their recombination. The heavily polluted area around NOA must account for the observed difference between the Mauna Loa results (Cobb, 1968) and those of NOA.

The results of multiple correlation between (a) conductivity and (b) large ion density and air pollution factors are demonstrated in Table 3. The correlation coefficients are considerable mainly during the winter months. The coefficient of determination, which stands for the percentage of variance of large ions due to the cumulative influence of sulfur dioxide, smoke and wind speed is variable being approximately 60%. The corresponding coefficient of determination for the conductivity is 42%.

5. Influence of Air Temperature and Relative Humidity on Conductivity

(a) In order to examine the possible influence of air temperature and relative humidity on the diurnal course of conductivity near the ground for all weather, we proceeded to linear correlation, for each month separately, based on mean hourly values.

Since temperature and relative humidity may exert an indirect influence, we proceeded to cross correlation with a lag time 0, 1, 2, and 3 hours (Table 4).

The contribution of these elements to the diurnal variation of the conductivity is considerable, especially during the warm months (April–September). Air temperature is positively while the relative humidity is negatively correlated to conductivity (owing perhaps to its inverse temperature dependence). The greatest influence is observed after a time lag of 3 hours.

These results are similar to those of D. Retalis and J. Zambakas (1975), who examined the influence of air temperature and relative humidity on small ion concentration variation except for a difference in the time lag. The corresponding influ-

Table 3. *Monthly Values of Multiple Correlation Coefficient Between Conductivity* (positive $R_{(\lambda+)}$ and negative $R_{(\lambda-)}$), *Large Ions* (positive $R_{(N+)}$ and negative $R_{(N-)}$) *and (1) Smoke, (2) Sulfur Dioxide and (3) Wind Speed*

	J	F	M	A	M	J	J	A	S	O	N	D
$R_{(\lambda+)}$	0.742	0.748	0.428	0.483	0.722	0.507	0.571	0.692	0.401	0.692	0.777	0.699
$R_{(\lambda-)}$	0.806	0.829	0.527	0.401	0.764	0.391	0.574	0.612	0.694	0.424	0.817	0.813
$R_{(N+)}$	0.858	0.745	0.765	0.709	0.656	0.736	0.843	0.897	0.707	0.597	0.866	0.894
$R_{(N-)}$	0.867	0.773	0.549	0.855	0.762	0.341	0.768	0.608	0.890	0.932	0.891	0.903

Table 4. *Correlation Coefficients* (with Lag-Time 0, 1, 2, and 3 hours) *of the Conductivity With Air Temperature and Relative Humidity for the Different Months*

	1. Air Temperature – Positive Conducivity				2. Air Temperature – Negative Conductivity			
Hours	0	1	2	3	0	1	2	3
J	– 0.156	– 0.046	0.025	0.054	– 0.317	– 0.256	– 0.226	– 0.213
F	0.102	0.259	0.345	0.358	– 0.091	0.006	0.065	0.080
M	0.244	0.436	0.566	0.616	0.017	0.182	0.307	0.362
A	0.448	0.640	0.764	0.804	0.298	0.470	0.560	0.606
M	0.188	0.394	0.559	0.669	0.365	0.503	0.597	0.633
J	0.392	0.610	0.768	0.859	0.403	0.555	0.640	0.671
J	0.277	0.484	0.643	0.758	0.274	0.406	0.500	0.564
A	0.295	0.482	0.619	0.715	0.308	0.412	0.473	0.502
S	0.196	0.376	0.509	0.608	0.242	0.356	0.428	0.480
O	0.084	0.268	0.402	0.493	– 0.143	– 0.032	0.053	0.120
N	0.334	0.477	0.549	0.556	– 0.028	0.043	0.068	0.056
D	– 0.152	– 0.026	0.059	0.105	– 0.241	– 0.188	– 0.181	– 0.180

	3. Relative Humidity – Positive Conductivity				4. Relative Humidity – Negative Conductivity			
Hours	0	1	2	3	0	1	2	3
J	0.135	0.018	– 0.054	– 0.078	0.289	0.222	0.193	0.189
F	– 0.095	– 0.241	– 0.322	– 0.337	0.086	0.007	– 0.043	– 0.051
M	– 0.274	– 0.438	– 0.528	– 0.545	– 0.046	– 0.164	– 0.239	– 0.274
A	– 0.407	– 0.609	– 0.743	– 0.794	– 0.288	– 0.467	– 0.561	– 0.612
M	– 0.163	– 0.367	– 0.533	– 0.647	– 0.336	– 0.471	– 0.575	– 0.625
J	– 0.383	– 0.603	– 0.763	– 0.855	– 0.395	– 0.548	– 0.634	– 0.667
J	– 0.247	– 0.459	– 0.624	– 0.748	– 0.263	– 0.399	– 0.499	– 0.567
A	– 0.280	– 0.474	– 0.611	– 0.708	– 0.313	– 0.424	– 0.482	– 0.507
S	– 0.145	– 0.343	– 0.492	– 0.611	– 0.211	– 0.350	– 0.442	– 0.515
O	– 0.059	– 0.255	– 0.403	– 0.509	0.130	0.017	– 0.071	– 0.143
N	– 0.268	– 0.433	– 0.539	– 0.588	0.067	– 0.016	– 0.059	– 0.068
D	0.168	0.054	– 0.029	– 0.081	0.239	0.202	0.202	0.199

ence on the large ions concentration is opposite (Retalis, 1983), since large ions are negatively correlated to air temperature and positively correlated to relative humidity.

The influence, after a time lag, of air temperature on the concentration of small ions and atmospheric conductivity may be explained as following: the radioactive matter existing in the air varies with time depending on the radioactive molecules diffused into the atmosphere and on the radioactivity emitted by the soil. This latter varies considerably, being influenced by many factors such as temperature, soil aridity, soil cover and wind speed. The radioactive matter diffused into the atmosphere depends on many factors too, mainly on turbulence (Wait and Parkinson, 1951). From the above, the indirect influence of air temperature on ions concentration near the ground may be explained. The influence of relative humidity is more ambiguous, since the particles begin to grow up when the relative humidity exceeds 65% (Junge, 1951).

(b) In order to examine the influence of air temperature and relative humidity on positive and negative conductivity, we proceeded to linear correlation for each month separately based on mean daily values for 13 years. No clear relationship appears, since the correlation coefficients are generally small, being larger for temperature during the winter months.

The influence of temperature and especially relative humidity on conductivity is generally unclear and widely varying (Dolezalek, 1978; Israel, 1971). Although Wright (1934) had related relative humidity to the effective radius of nuclei, the correlation of relative humidity to conductivity is more complex, due, among others, to its temperature dependence (Dolezalek, 1969).

In conclusion, we may say (a) the influence of air temperature and relative humidity on conductivity is generally weak, (b) their influence on the formation of the diurnal course of conductivity is important during the warm period (April–September) and (c) the maximum influence on conductivity appears with a 3 hour time lag.

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